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The Application Value of Transcranial Doppler Ultrasound in Cerebrovascular Diseases

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Abstract: *Cerebrovascular diseases (CVDs) are among the most prevalent disorders in the field of neurology. Given their high incidence and mortality rates, the accurate assessment of cerebral arterial hemodynamics is of crucial significance for the diagnosis and treatment of CVDs. Transcranial Doppler Ultrasound (TCD) is a non-invasive diagnostic modality for the detection of CVDs. Currently, the main application aspects of TCD in CVDs include the precise identification of diseased blood vessels, the evaluation of collateral circulation efficiency, and the investigation of cerebral blood flow autoregulation function. However, relatively few studies have been conducted on cerebral blood flow autoregulation function. This study primarily demonstrates that TCD and digital subtraction angiography (DSA) exhibit good consistency in the detection of intracranial collateral circulation patency, and that cerebral vascular hemodynamics is positively correlated with the degree of cerebral vascular stenosis. Meanwhile, in ischemic cerebrovascular disease (ICVD), the decrease in mean flow velocity (Vm) and the increase in pulsatility index (PI) in the vertebral artery and basilar artery can serve as potential evaluation indicators for this disease. The combination of TCD and color Doppler ultrasound enables more accurate assessment of the degree of vascular stenosis. The consistency of sensitivity, specificity, and accuracy between TCD combined with carotid artery ultrasound (CUS) and cerebral angiography in the diagnosis of transient ischemic attack (TIA) is relatively high. Meanwhile, the derived Breath-Holding Index (BHI, %/s) can be utilized as a risk assessment indicator for vascular cognitive impairment (VCI).*

Keywords: *Transcranial Doppler Ultrasound, Cerebrovascular Disease, Vascular Stenosis or Occlusion, Collateral Circulation, Cerebral Blood Flow Autoregulation Function*

1. Introduction

CVDs represent a general category of cerebral disorders caused by cerebral blood supply disturbances, which are mainly classified into ischemic cerebrovascular diseases, hemorrhagic cerebrovascular diseases, cerebral vascular stenosis or occlusion, intracranial vascular malformations, and other subtypes. TCD is a non-invasive detection technique for CVDs that leverages the ultrasonic Doppler effect to assess hemodynamic characteristics and physiological parameters of the basal cerebral arteries through the thin areas of the skull. TCD exhibits the following advantages: 1.Non-invasiveness: Compared with imaging modalities such as computed tomography (CT) and magnetic resonance imaging (MRI), it does not require contrast agents or ionizing radiation and can provide real-time dynamic hemodynamic data; 2.Reproducibility; 3.Continuous dynamic monitoring: It can conduct real-time hemodynamic assessment to reflect the dynamic process of blood flow and can be combined with functional tests (e.g., carotid compression test, carbon dioxide (CO_2) inhalation test), which enables dynamic evaluation of collateral circulation or vascular reactivity; 4.Capability to monitor organic cerebrovascular diseases and reflect changes in cerebrovascular function; Compact size, portability, and feasibility of bedside operation. The parameters measured by TCD include: Peak systolic velocity (PSV), End diastolic velocity (EDV), Mean flow velocity (Vm), calculated as $Vm = (1/3)PSV + (2/3)EDV$, Pulsatility index (PI), calculated as $PI = (PSV - EDV)/Vm$, Resistance index (RI), calculated as $RI = (PSV - EDV)/PSV$[1]. Currently, TCD can

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be used for the diagnosis of cerebral vascular stenosis, occlusion, and spasm[2]; furthermore, studies have confirmed that it exhibits high sensitivity in diagnosing the degree of cerebral vascular stenosis and occlusion[3]. The purpose of this study is to systematically evaluate the application value of TCD in CVDs, with a focus on its efficacy in assessing vascular stenosis, collateral circulation, and hemodynamics, as well as to explore its limitations and future research directions.

2. Main Text

2.1 Subarachnoid Hemorrhage

After aneurysmal subarachnoid hemorrhage (aSAH), cerebral vasospasm (CVS) occurs in as many as 50-90% of patients. Khawaja et al. aimed to compare computed tomography angiography (CTA) and TCD with DSA (the gold standard for early detection of CVS in patients with aSAH). They retrospectively included 7 studies and compared sensitivity, specificity, positive likelihood ratio (LR+), and negative likelihood ratio (LR−)[4]. Among these parameters, LR+ reflects the probability of an increased likelihood of the disease when the test result is positive, and an LR+ value higher than 10 is considered strong evidence for diagnosis; LR− reflects the probability of a decreased likelihood of the disease when the test result is negative, and an LR− value < 0.1 is regarded as strong evidence for ruling out the diagnosis. Compared with DSA, CTA exhibited a sensitivity of 82%, a specificity of 97%, an LR+ of 27.3, and an LR− of 0.19; TCD showed a sensitivity of 38%, a specificity of 91%, an LR+ of 4.22, and an LR− of 0.68. TCD had lower sensitivity and specificity than CTA in detecting CVS in aSAH patients, which may be associated with the fact that TCD mainly relies on mean flow velocity (MFV) as a surrogate for vascular diameter, thus failing to obtain an optimal ultrasound window. Among the two modalities, only the LR+ of CTA (> 10) met the clinical diagnostic criteria, while the LR− values of both CTA and TCD were close to the threshold of clinical significance for ruling out the diagnosis. In terms of CVS diagnosis, CTA demonstrated a higher LR+ and a lower LR− than TCD; therefore, CTA is strongly recommended for diagnosing or ruling out CVS. For patients in whom CVS is still suspected despite normal TCD velocity test results, CTA can be used, with supplementary electroencephalography (EEG) and multimodal monitoring.

Aaslid et al. aimed to use TCD to monitor the mean velocity (Vm, cm/s) of the middle cerebral artery (MCA), anterior cerebral artery (ACA), and posterior cerebral artery (PCA)[5]. They retrospectively enrolled 50 healthy individuals who underwent physical examinations into the study; the Vm of MCA was 62±12 cm/s, ACA was 51±12 cm/s, PCA was 44±11 cm/s, and extracranial internal carotid artery (ICA) was 37±6.5 cm/s. The Vm of ACA and PCA was generally lower than that of MCA but higher than that of extracranial ICA, which indicates that the velocity of the basilar artery is the highest in the cerebral circulation of healthy individuals. The Vm of MCA provides direct information on the relative changes in volumetric flow during ICA occlusion. When arterial constriction or luminal stenosis occurs, Vm is inversely proportional to the vascular luminal area. It suggests that the Vm of the basilar artery can be recorded to evaluate CVS. Although DSA remains the standard method for evaluating CVS, it is an invasive technique and cannot be repeatedly performed frequently. This indicates that TCD can be used for CVS monitoring and has high clinical application value.

Qi et al. aimed to explore the value of TCD in delayed cerebral ischemia (DCI) after aSAH[6]. A total of 54 patients were retrospectively enrolled in the study, with the observation endpoint set as 14 days after the onset of the disease or the occurrence of DCI; the patients were divided into the DCI group (16 cases) and the non-DCI group (38 cases). SPSS 25.0 software, t-test, chi-square test (χ^2 test), and Logistic regression analysis were used for data analysis. In the DCI group, PSV, EDV, Vm, and PI of the MCA were 139.4±38.5, 52.7±8.2, 81.8±17.9, and 1.03±0.18, respectively; in the non-DCI group, the aforementioned parameters were 103.1±15.3, 48.5±7.3, 65.1±10.1, and 0.84±0.12, respectively. The PSV, EDV, Vm, and PI of MCA in the non-DCI group were significantly lower than those in the DCI group. Logistic regression analysis showed that Vm had high predictive value for DCI in aSAH patients; therefore, TCD can be used early to monitor hemodynamics for detecting DCI. Additionally, it was found that the onset of DCI in the DCI group was concentrated within 2–6 days after aSAH, which provides reference value for exploring and determining the minimum time window for DCI occurrence, and can shorten the monitoring time and improve patient compliance. However, this study was a single-center study with a small sample size, and no analysis was conducted on blood vessels other than the MCA. Further verification of the conclusions of this study with multi-center collaboration and an expanded sample size is still needed, and more predictive indicators should be actively explored.

Schenck et al. aimed to compare the predictive value of TCD-derived biomarkers for DCI[7]. A total of 23 articles were retrospectively included in the study to compare the sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) of cerebral blood flow velocities (CBFV), cerebral autoregulation (CA), and microembolic signals (MES). Among these parameters, LR = MFV of MCA / MFV of the ipsilateral extracranial internal carotid artery is used to assess the presence of arterial stenosis; for CA assessment, one method is the transient hyperemic response test (THRT), and the other methods are the systolic blood flow index (Sxa) and mean blood flow index (Mxa). The sensitivity and specificity of predicting DCI using different CBFV thresholds were 0.47 and 0.80, respectively; for CBFV combined with LR > 3, the sensitivity, specificity, PPV, and NPV were 0.86, 0.75, 0.58, and 0.91, respectively; for THRT, the aforementioned values were 0.87, 0.81, 0.64, and 0.95, respectively; for Mxa, they were 0.67, 0.75, 0.40, and 0.90, respectively; and for Sxa, the corresponding values were 0.81, 0.76, 0.62, and 0.89, respectively; for MES, the values were 0.61, 0.74, 0.59, and 0.73, respectively. A comparison of the three aforementioned biomarkers showed that CBFV is the most commonly used TCD-derived indicator for predicting DCI in patients with aSAH. When combined with LR > 3 to predict clinical and/or radiological DCI, the highest sensitivity can be achieved; however, TCD-derived biomarkers for CA showed the highest sensitivity and specificity for DCI prediction. The overall sensitivity and specificity of MES monitored by TCD were relatively low. In general, an increase in CBFV as an indicator of DCI has high sensitivity and specificity, and thus exhibits high predictive value for DCI.

2.2 Cerebrovascular and Cervical Vascular Stenosis

Intracranial arterial stenosis, especially severe stenosis of the MCA and ACA, leads to reduced cerebral blood flow and can cause serious clinical consequences. Zheng et al. aimed to explore the value of TCD in monitoring cerebrovascular stenosis[8]. A total of 60 patients were retrospectively enrolled in the study, and SPSS 21.0 software, t-test, and Pearson correlation analysis were used for data analysis. DSA confirmed 25 cases of moderate stenosis and 35 cases of severe stenosis. In patients with moderate stenosis, the blood flow velocities (cm/s) of the left middle cerebral artery (LMCA), right middle cerebral artery (RMCA), left anterior cerebral artery (LACA), and right anterior cerebral artery (RACA) were 104.15±11.15 (r=0.341), 98.85±9.25 (r=0.331), 95.56±9.36 (r=0.295), and 101.14±10.75 (r=0.304); in patients with severe stenosis, the blood flow velocities of the aforementioned arteries were 117.45±12.25 (r=0.475), 114.86±10.45 (r=0.455), 114.41±11.06 (r=0.401), and 121.15±13.25 (r=0.413). The blood flow velocities of LMCA, RMCA, LACA, and RACA in patients with severe cerebrovascular stenosis were significantly faster than those in patients with moderate stenosis. The blood flow velocity of cerebrovascular stenosis was positively correlated with the degree of stenosis, and the correlation was stronger in severe stenosis. Vascular stenosis leads to a reduction in the inner diameter of blood vessels, and the blood flow velocity accelerates when passing through the stenotic segment; therefore, the degree of vascular stenosis can be inferred through blood flow velocity.

Ma et al. aimed to explore the value of TCD in evaluating collateral circulation in patients with severe MCA stenosis[9]. A total of 62 patients with severe MCA stenosis were retrospectively enrolled and divided into the symptomatic group and asymptomatic group based on the presence or absence of cerebral ischemic symptoms and neurological dysfunction. SPSS 25.0 software, t-test, and χ^2 test were used for data analysis. The opening rate of collateral circulation in the symptomatic group was significantly lower than that in the asymptomatic group. The anterior communicating artery (ACoA) and posterior communicating artery (PCoA) had relatively high opening rates, serving as the hub of collateral circulation and playing an important role in cerebral ischemia. The studies by Xie Ping et al. and CONNOLLY et al. aimed to explore the value of TCD in the opening of intracranial collateral circulation after severe unilateral internal carotid artery (ICA) stenosis or occlusion[10-12]. A comparison between the two studies showed that the opening rates of ACoA and ophthalmic artery (OA) in the latter were significantly higher than those in the former, while the opening rate of PCoA in the latter was significantly lower than that in the former; this difference may be related to the integrity of the cerebral Circle of Willis. In the study by Fang Mengxiao, TCD showed high coincidence rate and consistency with DSA in evaluating the opening of ACoA, PCoA, and OA, with kappa values of 0.84, 0.78, and 0.66, respectively[13]. TCD determines collateral opening by monitoring the blood flow direction and blood flow spectrum of collaterals. (the specific data comparison is shown in Table 1). TCD has high consistency with DSA in evaluating intracranial collateral circulation, and thus exhibits high value in assessing intracranial collateral circulation after severe unilateral ICA stenosis or occlusion[14].

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Table 1: Comparison of collateral circulation detection rates by TCD

Research group	Parameter / Project	ACoA (%)	PCoA (%)	OA (%)
Ma	Symptomatic group	15.00	15.00	10.00
	Asymptomatic group	36.36	31.82	31.82
Xie	TCD	73.00	73.00	59.00
CONNOLLY	TCD	81.00	53.00	63.00
Fang	TCD	93.10	91.00	80.70

Bai et al. aimed to compare the value of TCD and DSA in detecting cerebral arterial stenosis[15]. A total of 80 patients were retrospectively selected and enrolled in the study, and SPSS 24.0 software and χ^2 test were used for data analysis. For TCD, the stenosis rates were 31.25% for the left vertebral artery, 23.75% for the right vertebral artery, and 21.25% for the basilar artery; for DSA, the stenosis rates were 25.00% for the left vertebral artery, 20.00% for the right vertebral artery, and 17.50% for the basilar artery. TCD detects blood vessels in the anterior and posterior cerebral circulations. It analyzes parameters such as blood flow velocity, direction, and spectral morphology, and makes corresponding judgments on lesion conditions. DSA judges whether there is cerebrovascular occlusion or stenosis by comparing the distribution of contrast agents. TCD has a higher detection rate of vascular stenosis and can effectively judge the status of cerebrovascular stenosis. Yu et al. took DSA as the gold standard to explore the value of TCD in intracranial vascular stenosis[16]. The coincidence rate between TCD and DSA in diagnosing the degree of cerebrovascular stenosis was 92.79%, which suggests that TCD has high accuracy in the diagnosis of cerebrovascular stenosis. Although it cannot completely replace DSA examination, TCD has advantages such as intuitiveness, safety, and simple operation, and thus has certain value in the diagnosis of cerebrovascular stenosis.

Wu et al. aimed to explore the value of TCD and color Doppler ultrasound in the diagnosis of cervical vascular stenosis[17]. A total of 72 patients were retrospectively selected and enrolled in the study. According to the North American Symptomatic Carotid Endarterectomy Trial (NASCET) classification, the patients were divided into mild, moderate, and severe stenosis groups[18]. Data were analyzed by using SPSS 23.0 software, t-test, Kappa test, and other methods. The accuracy rate of TCD was 79.76%, while that of color Doppler ultrasound was 86.90%. TCD had a lower accuracy rate than color Doppler ultrasound in the diagnosis of mild stenosis; however, TCD was superior to color Doppler ultrasound in the diagnosis of moderate stenosis, severe stenosis, and occlusion. Color Doppler ultrasound provides real-time color images of blood flow velocity and direction, whereas TCD can monitor the blood flow of intracranial vessels. It is recommended that the combination of the two methods not only enables the observation of vascular stenosis but also helps understand the hemodynamic changes of blood vessels, which is conducive to more accurately evaluating the degree of vascular stenosis.

An et al. aimed to explore the value of CUS combined with TCD in the diagnosis of ischemic stroke[19]. A total of 100 patients with confirmed ischemic stroke were retrospectively selected and enrolled in the study. Data were analyzed using SPSS 22.0 software, t-test, and χ^2 test. In this study, the detection rate of carotid artery stenosis severity by combined diagnosis was significantly higher than that by single diagnosis, (the specific data comparison is shown in Table 2), which was consistent with the results of previous studies[20, 21]. CUS helps determine plaque conditions by measuring arterial lumen diameter and vascular wall thickness; TCD identifies intracranial vascular lesions based on the Doppler effect, but has limitations in detecting vulnerable plaques of intracranial arteries and variant blood vessels. The combination of the two methods enables comprehensive judgment of vascular stenosis severity, and further reduces the misdiagnosis rate by integrating indicators such as echo and blood flow.

ISSN 2618-1584 Vol. 7, Issue 6: 58-69, DOI: 10.25236/FMSR.2025.070607

Table 2: Comparison of detection rates for vascular stenosis severity

Research group	Classification / Project	Mild stenosis (%)	Moderate stenosis (%)	Severe stenosis (%)	Occlusion (%)
Bai	TCD	11.25	37.50	30.00	5.00
	DSA	2.50	25.00	22.50	1.25
Yu	TCD	21.95	19.51	24.39	17.89
	DSA	25.78	28.13	23.44	22.66
Wu	TCD	25.00	44.04	21.43	9.52
	Color Doppler ultrasound	29.76	42.86	19.05	8.33
An	TCD	23.00	25.00	13.00	4.00
	CUS	20.00	23.00	12.00	3.00
	Combination	33.00	35.00	25.00	7.00
Ma	TCD	48.56	27.54	15.22	8.70
	CUS	47.26	27.40	15.75	9.60

Xiao et al. aimed to analyze the intracranial arterial blood flow parameters in severe stenosis of the extracranial internal carotid artery (EICA) using TCD[22]. A total of 63 patients were retrospectively selected and enrolled in the study, and divided into the symptomatic group and asymptomatic group based on clinical manifestations and examination results. DSA confirmed the stenosis severity as follows: mild stenosis (arterial inner diameter reduction < 30%), moderate stenosis (30–69%), severe stenosis (70–99%), and complete occlusion (100%). Data were analyzed using SPSS 23.0 software, t-test, F-test, and other methods. The PSV, EDV, Vm, and PI in patients with severe stenosis were lower than those in patients with moderate and mild stenosis, indicating that the more severe the stenosis, the more obvious decrease in blood flow parameters. A decrease in Vm can indirectly reflect a reduction in cerebral perfusion level; the more severe the stenosis, the greater the resistance to cerebral blood flow, leading to a decrease in blood flow velocity. The PSV, EDV, Vm, and PI in symptomatic patients with severe stenosis were lower than those in asymptomatic patients with severe stenosis, suggesting that patients with severe stenosis do not necessarily have significant hemodynamic changes, and such changes may be related to collateral circulation to a certain extent.

Li et al. aimed to study the value of TCD in evaluating the degree of ICA stenosis and its influence on collateral circulation[23]. A total of 96 patients with confirmed ICA stenosis were retrospectively selected and enrolled in the study. SPSS 23.0 software and t-test were used for data analysis, and parameters including PSV, PI, and cerebrovascular reserve (CVR) were recorded. According to the NASCET classification[18], the patients were divided into mild, moderate, and severe stenosis groups; based on the TCD evaluation criteria for collateral circulation opening, the patients were categorized into the collateral circulation group and non-collateral circulation group[24]. The results of DSA showed the following collateral circulation opening rates: ACoA 35.19%, PCoA 31.48%, and external-internal carotid collateral 33.33%; the results of TCD showed the following opening rates: ACoA 31.48%, PCoA 29.64%, and external-internal carotid collateral 29.63%(the specific data comparison is shown in Table 3). With the increase in ICA stenosis, the ipsilateral perfusion pressure decreased, leading to a reduction in cerebrovascular reserve capacity, and consequently, PSV, PI, and CVR decreased. PSV, PI, and CVR were negatively correlated with the degree of stenosis. After ICA stenosis or occlusion, collateral circulation is established, and blood flows to the affected side through the anterior cerebral artery and ACoA, which can improve cerebrovascular reserve perfusion capacity and blood flow velocity. The PSV, PI, and CVR in the collateral circulation group were significantly higher than those in the non-collateral circulation group. There was no statistical significance in the detection rate of collateral circulation opening between TCD and DSA, indicating that TCD has high diagnostic value in ICA stenosis.

Table 3: Comparison of Hemodynamic Parameters in Cervical Vascular Stenosis

	Parameter / Classification		PSV(cm/s)	EDV(cm/s)	PI	Vm(cm/s)
Xiao	Mild stenosis		59.57±6.79	34.26±3.29	0.79±0.18	57.25±6.38
	Moderate stenosis		51.32±5.64	30.47±5.16	0.71±0.15	46.74±5.45
	Severe stenosis		42.45±8.28	25.75±3.23	0.56±0.12	39.53±6.43
	Symptomatic group		38.67±7.26	21.38±3.44	0.53±0.14	36.75±7.23
	Asymptomatic group		51.51±7.23	33.12±3.69	0.70±0.15	48.41±9.45
Li	Index / Stenosis degree			PSV(cm/s)	PI	CVR(%)
	Mild stenosis			67.84±7.25	0.64±0.17	21.35±1.93
	Moderate stenosis			58.24±6.31	0.53±0.13	18.27±1.69
	Severe stenosis			49.35±5.76	0.46±0.11	13.43±1.35

Huang et al. aimed to explore the diagnostic value of TCD in the establishment of collateral circulation for extracranial internal carotid artery (ICA) lesions[25]. A total of 175 patients were retrospectively selected and enrolled in the study, and SPSS 22.0 software, t-test, and χ^2 test were used for data analysis. With DSA as the gold standard: 125 cases had ACoA opening, 88 cases had PCoA opening, and 76 cases had extracranial ICA opening. For TCD: 86 cases had ACoA opening, with a sensitivity of 64.80%, specificity of 90.00%, and accuracy of 72.00%; 98 cases had PCoA opening, with a sensitivity of 89.77%, specificity of 78.16%, and accuracy of 84.00%; 74 cases had extracranial ICA opening, with a sensitivity of 88.16%, specificity of 92.93%, and accuracy of 90.86%. The collateral opening rate was 72% in patients with mild-to-moderate stenosis and 90% in patients with severe stenosis or occlusion;[20] the collateral circulation opening rate in patients with severe stenosis or occlusion was higher than that in patients with mild-to-moderate stenosis. TCD showed high sensitivity, specificity, and accuracy in the diagnosis of extracranial ICA opening, and could identify lesion vessels by detecting blood flow velocity, direction, and spectral morphology. Meanwhile, the carotid compression test was used to evaluate the opening status of ACoA. The relatively low sensitivity and accuracy of ACoA detection by TCD were considered to be related to the operator's technique and the anatomical course of ACoA. When local vascular ischemia occurs, collateral circulation is opened to provide adequate blood supply; therefore, the more severe the stenosis, the higher the collateral circulation opening rate. TCD has application value in evaluating the establishment of collateral circulation for extracranial ICA lesions and can be used as an important method for assessing collateral circulation establishment.

2.3 Ischemic Cerebrovascular Disease

It is worth noting that ICVD is a clinically common cerebrovascular disease with high disability rate and mortality rate. Chen et al. aimed to explore the diagnostic value of CUS combined with TCD in ICVD[26]. A total of 364 patients were retrospectively selected as the observation group, and 360 healthy individuals were selected as the control group for inclusion in the study. The Vm and PI of the vertebral artery and basilar artery were recorded, and data were analyzed using SPSS 19.0 software, t-test, and χ^2 test. In the observation group, the vertebral artery Vm (cm/s), vertebral artery PI, basilar artery Vm (cm/s), and basilar artery PI were 20.54±4.60, 1.24±0.30, 31.76±4.66, and 1.33±0.30, in the control group, the aforementioned parameters were 28.63±6.70, 0.84±0.24, 45.64±7.81, and 0.83±0.11, respectively. The Vm of the vertebral artery and basilar artery in the observation group was lower than that in the control group, while the PI of the vertebral artery and basilar artery in the observation group was higher than that in the control group. This result was consistent with the findings of previous studies, indicating that the decrease in Vm and increase in PI of the vertebral artery and basilar artery can be used as diagnostic indicators for ICVD[27].

Chen et al. aimed to explore the diagnostic efficacy of combined TCD and CUS examination in ICVD[28]. A prospective study was conducted on 100 patients with suspected ischemic stroke, and SPSS 24.0 software and χ^2 test were used for data analysis. Previous studies have shown that the accuracy, sensitivity, and specificity of combined CUS and TCD in ischemic stroke are higher than those of either examination alone (the specific data comparison is shown in Table 4), which is consistent with the findings of this study[19, 29]. TCD detects the blood flow velocity and hemodynamic changes of intracranial vessels, enabling accurate identification of intracranial vascular stenosis, occlusion, spasm, and other conditions in ICVD; CUS detects the blood flow velocity of carotid arteries, which can accurately determine the severity of ICVD. The combined use of TCD and CUS allows for the assessment of intracranial vascular blood flow velocity and spectral information, thereby effectively improving the diagnostic value. Studies by Shen et al. have confirmed that contrast-enhanced carotid ultrasound combined with TCD can also improve sensitivity, specificity, and accuracy[30]. Contrast-enhanced carotid ultrasound not only enables real-time dynamic perfusion imaging but also has high resolution, which can make up for the limitations of TCD. However, TCD provides a non-invasive examination for carotid artery diseases and is widely applicable to various populations. The two methods complement each other, and their combined application improves diagnostic efficacy.

Table 4: Comparison of Diagnostic Efficacy Among Different Examinations

Research group	Parameter / Project	Sensitivity (%)	Specificity (%)	Accuracy (%)
Chen	CUS	75.71	66.67	73.00
	TCD	80.00	70.00	77.00
	Combined diagnosis	92.86	90.00	92.00
An	CUS	81.00	83.00	88.00
	TCD	85.00	84.00	89.00
	Combined diagnosis	94.00	95.00	98.00
Xiong	CUS	75.83	64.17	70.00
	TCD	70.83	65.85	68.33
	Combined diagnosis	94.17	89.17	91.67
Shen	Contrast-enhanced carotid ultrasound	89.53	57.14	85.00
	TCD	86.05	78.57	85.00
	Combined diagnosis	97.67	92.86	97.00

Zhou et al. aimed to analyze the value of combined TCD and CUS in the evaluation of intracranial vessels in patients with ICVD[31]. A total of 41 patients with ischemic stroke were retrospectively selected as the observation group, and another 41 patients without ischemic stroke were selected as the control group in the study. SPSS 22.0 software, t-test, and χ^2 test were used for data analysis. In the observation group: the rate of intracranial vascular stenosis was 100.00%, including 9.76% with mild stenosis, 29.27% with moderate stenosis, and 60.98% with severe stenosis or occlusion; in the control group: the rate of intracranial vascular stenosis was 46.34%, including 39.02% with mild stenosis, 7.32% with moderate stenosis, and 0.00% with severe stenosis or occlusion. The degree of intracranial vascular stenosis in the observation group was significantly higher than that in the control group. TCD reflects the functional status of cerebral vessels by obtaining hemodynamic parameters of cerebral arteries, while CUS realizes the evaluation of vascular stenosis severity through the observation of cervical vessels[20]. The combination of the two methods can more accurately evaluate vascular lesions.

ISSN 2618-1584 Vol. 7, Issue 6: 58-69, DOI: 10.25236/FMSR.2025.070607

Zhou aimed to systematically evaluate the role of TCD in the diagnosis of ICVD[32]. Retrospective studies on TCD for diagnosing ICVD at home and abroad were collected, and a total of 11 literatures were included for Meta-analysis. Risk of bias analysis was performed on the included literatures, and diagnostic analysis was conducted using the summary receiver operating characteristic (SROC) curve. The results showed that the sensitivity of TCD was 0.93 and the specificity was 0.95, but the area under the curve (AUC) of the SROC curve was 0.887, indicating a moderate effectiveness. TCD is affected by factors such as operator technique and cerebrovascular activity. Although DSA is the gold standard for diagnosing ICVD, it has limitations including invasiveness, operational difficulty, and restricted clinical application. CTA can display the shape of blood vessels through contrast agents and is used for the diagnosis of occlusion or stenosis. Compared with CTA, the sensitivity and specificity of TCD in diagnosing arterial occlusion in ischemic stroke both exceed 90%. Although TCD cannot perform accurate non-invasive monitoring or provide direct imaging results, it remains the only available non-invasive method for detecting cerebral hemodynamic changes.

2.4 Transient Ischemic Attack

TIA is a transient, reversible, and localized cerebral circulatory disorder that occurs under the condition of atherosclerosis, and it is a prodromal manifestation of cerebral infarction[33]. Ban et al. aimed to explore the application value of combined TCD and CUS in TIA[34]. A total of 100 patients with suspected TIA were retrospectively enrolled in the study. SPSS 22.0 software and χ^2 test were used for data analysis. With cerebral angiography as the "gold standard", the positive detection rate of cerebral angiography was 80.00%. For the combined diagnosis: the positive detection rate was 80.00%, sensitivity was 98.75%, accuracy was 98.00%, specificity was 95%, and kappa = 0.938. Although cerebral angiography has high diagnostic value for TIA, it is an invasive procedure and relatively expensive. In this study, the positive detection rate, sensitivity, accuracy, and specificity of combined CUS and TCD were compared with those of cerebral angiography; the results showed a high consistency between the two methods. Therefore, the combined diagnosis of TCD and CUS can be applied to the diagnosis of TIA.

2.5 Cerebral Infarction

CI is a typical cerebrovascular disease, with the main pathological change being irreversible necrosis of brain cells in the blood supply area caused by cerebrovascular occlusion; the prognosis of patients with cerebral infarction is poor. Chen et al. aimed to explore the value of color Doppler ultrasound (CDU) combined with TCD in evaluating the degree of carotid artery stenosis in acute CI[35]. A total of 65 patients were retrospectively selected in the study, and SPSS 21.0 software and χ^2 test were used for data analysis. With DSA as the gold standard, the incidence of carotid artery stenosis was 76.92%, including 36.00% with mild stenosis, 34.00% with moderate stenosis, and 30.00% with severe stenosis or complete occlusion. CDU can evaluate the anatomical structure of cervical vessels and hemodynamic parameters, and obtain the PSV and EDV of the internal carotid artery. TCD measures the hemodynamics of the internal carotid artery and blood parameters; the PI and RI reflect hemodynamic changes in the proximal and distal segments of the stenotic vessel and are used to evaluate the degree of carotid artery stenosis. The RI is positively correlated with the degree of carotid artery stenosis, while PSV, EDV, and PI are negatively correlated with the degree of carotid artery stenosis[20]. The degree of carotid artery stenosis can be determined by the changes in PSV, EDV, PI, and RI, which has extremely high application value for evaluating the degree of carotid artery stenosis in acute CI.

Lei et al. explored the value of TCD in patients with severe acute CI[36]. A total of 79 patients with severe acute CI were retrospectively enrolled as the research subjects, and 50 healthy individuals who underwent physical examination were selected as the control group. The modified Rankin Scale (mRS) was used to evaluate the short-term prognosis of patients, who were divided into the poor prognosis group and good prognosis group[37]. SPSS 21.0 software, t-test, and χ^2 test were used for data analysis. The MCA is the most commonly used blood vessel for evaluating cerebral blood supply; PSV, EDV, and Vm are indicators reflecting blood flow velocity; PI is related to changes in vascular elasticity and resistance, and an increase in PI often indicates insufficient distal perfusion. The PSV, EDV, and Vm in both the good prognosis group and the poor prognosis group were lower than those in the control group, while there was no significant difference in PI. This suggests that simple detection of cerebral hemodynamics cannot effectively evaluate the prognosis of patients with cerebral infarction.

Gao et al. aimed to explore the value of TCD in patients with CI[38]. A total of 2800 patients with CI were retrospectively selected and enrolled in the study, and divided into the mild group, moderate group, and severe group according to the National Institutes of Health Stroke Scale (NIHSS)[39]. SPSS 20.0 software, t-test, F-test, and χ^2 test were used for data analysis. The Vm of the ACA, MCA, and PCA in the severe group was lower than that in the mild group and moderate group, while the PI and RI in the severe group were higher than those in the moderate group and mild group. This indicates that patients with severe cerebral infarction have lower cerebral blood flow velocity and higher PI and RI. TCD can accurately reflect pathological states such as cerebral artery stenosis, spasm, and infarction, as well as differences in cerebral hemodynamic parameters among patients with CI, thereby providing a relatively reliable reference for the diagnosis and condition assessment of cerebral infarction.

Wang et al. aimed to explore the value of TCD in evaluating cognitive impairment in patients with acute cerebral infarction (CI)[40]. A total of 91 patients were retrospectively enrolled in the study, and the cerebral hemodynamic index (BHI, %/s) was calculated based on Vm. The Montreal Cognitive Assessment (MoCA) scale was used to divide the patients into the acute-phase cognitive impairment group and non-acute-phase cognitive impairment group; according to the evaluation results of secondary vascular cognitive impairment (VCI), the patients were further classified into three categories: normal, mild VCI, and vascular dementia (VaD). SPSS 22.0 software and t-test were used for data analysis. The BHI values were as follows: 0.50±0.17 in the acute-phase cognitive impairment group, 0.72±0.19 in the non-acute-phase cognitive impairment group, 0.73±0.18 in the normal vascular group, 0.52±0.15 in the mild VCI group, and 0.50±0.10 in the vascular dementia group. The MoCA score was negatively correlated with the PI of the MCA ($r=-0.561$), and positively correlated with Vm ($r=0.612$) and BHI ($r=0.628$). These results suggest that the PI, Vm, and BHI of the MCA are correlated with cognitive impairment after CI; abnormal levels of these parameters indicate an increased risk of secondary VCI. Therefore, the Vm and BHI of the middle cerebral artery can be used as risk assessment indicators for secondary VCI.

3. Conclusions

This article currently explores the application value of TCD in five types of diseases: SAH, cervical and cerebrovascular stenosis, ICVD, TIA, and CI. In SAH, the cerebral hemodynamic parameters of TCD have led to the derivation of the indicator of DCI; exploring and determining the minimum time window for DCI occurrence can shorten the monitoring duration and save medical resources. In cervical and cerebrovascular stenosis, the hemodynamics of cerebral vessels are positively correlated with the degree of stenosis: the more severe the stenosis, the more significant the decrease in hemodynamic parameters. However, hemodynamic changes may not be obvious in patients with severe stenosis, which may be related to the opening of collateral circulation. TCD shows high consistency with DSA in evaluating intracranial collateral circulation. Compared with DSA, TCD can be combined with ultrasound image analysis, resulting in a higher detection rate of cerebrovascular stenosis. It not only enables the observation of hemodynamic changes in cerebral vessels but also has the advantages of intuitiveness, safety, and simplicity of operation. CDU provides real-time color images of blood flow velocity and direction, intuitively displaying hemodynamic information, while TCD can monitor the blood flow of intracranial vessels; the combination of the two methods allows for more accurate evaluation of the degree of vascular stenosis and improves diagnostic accuracy. CUS helps determine the status of plaques by measuring the diameter of the arterial lumen and the thickness of the vessel wall, while TCD identifies intracranial vascular lesions through the Doppler effect. However, TCD has limitations in detecting vulnerable plaques and variant intracranial arteries; the combination of the two methods enables a comprehensive assessment of the degree of vascular stenosis and improves the detection rate. In ICVD, the decrease in Vm and increase in PI of the vertebral artery and basilar artery can be used as diagnostic indicators for ICVD. The sensitivity and specificity of combined TCD and CUS are higher than those of either single examination, allowing for a comprehensive evaluation of cerebrovascular conditions and the degree of stenosis. Contrast-enhanced carotid ultrasound not only enables real-time dynamic perfusion imaging but also has high resolution, which can make up for the limitations of TCD. In contrast, TCD provides non-invasive examination for carotid artery diseases, and the combination of the two methods improves diagnostic efficacy. Cerebral angiography has high diagnostic value for TIA but is an invasive procedure and relatively expensive. A comparison of the positive detection rate, sensitivity, accuracy, and specificity between combined CUS and TCD and cerebral angiography showed high consistency, indicating that the combined diagnosis of TCD and CUS can be applied to the diagnosis of TIA. In CI, TCD can accurately reflect pathological states such as cerebral artery stenosis, spasm, and infarction, as well as differences in cerebral hemodynamic parameters among patients with cerebral infarction, thereby providing a relatively reliable reference for the diagnosis and condition assessment. However, simple detection of cerebral hemodynamics cannot effectively evaluate the prognosis of patients with cerebral infarction. On this basis, Wang Peng et al. derived the cerebral hemodynamic index (BHI)[40]. The PI, Vm, and BHI of the MCA are correlated with cognitive impairment after cerebral infarction; abnormal levels of these parameters indicate an increased risk of secondary VCI. Therefore, the Vm and BHI of the MCA can be used as risk assessment indicators for secondary VCI.

However, TCD also has limitations: 1. Strong dependence on operator technique: The identification of blood vessels and adjustment of angles require the examiner to have extensive knowledge of cerebrovascular anatomy and clinical practice, as well as proficient operational skills. 2. Inability to directly display the anatomical structure of blood vessels. 3. Relatively low sensitivity in detecting posterior circulation lesions (e.g., vertebrobasilar artery system). In the previous content, the discussion mainly focused on the role of TCD in vascular stenosis and collateral circulation, while literature related to cerebral blood flow autoregulation was not mentioned. Further research on this aspect is needed to better explore the application value of TCD in cerebrovascular diseases. Currently, artificial intelligence assisted analysis technology is becoming increasingly mature, and it can be applied to the field of TCD and cerebrovascular diseases.

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