REVIEW ARTICLE

Applications of Carotid Ultrasound and Transcranial Color-coded Sonography/Transcranial Doppler in Carotid Artery Revascularization

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Abstract: Stroke stands as a leading cause of mortality worldwide, with carotid artery stenosis being a major factor of ischemic stroke. Carotid endarterectomy (CEA) and carotid artery stenting (CAS) are the primary revascularization strategies for this condition. Imaging methods play a pivotal role in providing clinicians and surgeons with crucial information, aiding in diagnosis, risk stratification, peri-operative evaluation, and post-surgical follow-up of patients. This review summarizes the literature available in the PubMed database from the past 25 years and discusses current research investigating the applications of carotid duplex ultrasonography (CDU), transcranial color-coded sonography (TCCS), and transcranial Doppler (TCD) in the revascularization of carotid arteries.

Key words: Carotid endarterectomy; Carotid artery stenting; Carotid duplex ultrasonography; Transcranial color-coded sonography; Transcranial Doppler

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Atherosclerotic carotid artery stenosis is the leading cause of ischemic stroke and, a major contributor to mortality rates worldwide [1,2]. Carotid endarterectomy (CEA) and carotid artery stenting (CAS) are the primary revascularization strategies for carotid artery stenosis. Several clinical trials, including the North American Symptomatic Carotid Endarterectomy Trial (NASCET), European Carotid Surgery Trial (ECST), and Asymptomatic Carotid Surgery Trial (ACST), have demonstrated the efficacy of CEA in the treatment of both symptomatic and asymptomatic patients with carotid artery stenosis [3-5]. Recently, CAS has emerged as a viable alternative approach to CEA in the management of carotid artery stenosis [6]. Meanwhile, noninvasive imaging methods, such as carotid duplex ultrasound (CDU), computed tomography (CT)/CT angiography (CTA), and magnetic resonance imaging (MRI)/magnetic resonance angiography (MRA), have been widely and routinelyapplied in clinical practice to provide valuable information to clinicians and surgeons and assist in the assessment, categorization of risk, perioperative evaluation, and monitoring of patients after surgery. This review focuses on the applications of CDU, transcranial color-coded sonography (TCCS), and transcranial Doppler imaging (TCD) for carotid artery revascularization. We searched the relevant literature from the PubMed database over the past 25 years and summarized them as follows.

Stroke and Carotid Artery Stenosis

Approximately 20% of stroke casesare caused by extracranial carotid artery stenosis [7]. The etiology of carotid artery stenosis or occlusion includes atherosclerosis, dissection, fibromuscular dysplasia, Takayasu arteritis, embolism, neck irradiation, and carotid web, with atherosclerotic stenosis being the most common cause of stroke. The mechanisms underlying carotid

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artery steno-occlusive diseases that induce stroke include artery-artery embolization and hypoperfusion of the cerebral blood flow [2,7]. The severity of carotid artery stenosis is closely associated with stroke risk [8]. Furthermore, the evaluation of atherosclerotic plaque stability is equally crucial in the evaluation of the degree of stenosis, because unstable plaques are the primary source of micro-emboli [2,7].

Carotid Artery Revascularization Strategies

CEA and CAS are the primary revascularization strategies used to treat carotid artery stenosis. According to the most recent recommendations of European Society of Vascular Surgeons (ESVS), CEA should be considered for asymptomatic patients with 60-99% stenosis, provied the risk of stroke or death within 30 days is less than 3% and the patient is expected to live for at least 5 years. In such cases, CAS may be considered a viable alternative to CEA. CEA is advisable for symptomatic patients with 50-99% carotid artery stenosis within the past 6 months, provided that the 30-day risk of death/stroke is less than 6%. For patients aged < 70 years, CAS can also be considered as an alternative treatment option [9].

Several large-sample trials, including the CAVATS, SAPPHIRE, ICSS, EVA-3S, and CREST-1 trials, have compared the efficacy, and different duration of outcomes following CEA and CAS in individuals with carotid artery narrowing, showing variable results [10]. The newly published CREST-2 trial showed that among patients with high-grade stenosis without recent symptoms, the addition of CAS led to a lower risk of a composite of perioperative stroke or death or ipsilateral stroke within 4 years compared with intensive medical management alone (2.8% *vs.* 6.0%, $P = 0.02$). CEA did not lead to a significant benefit (3.7% vs. 5.3%, $P = 0.24$) [11]. A transcarotid artery revascularization (TCAR) device was approved in 2015 for patients at a high risk of stroke, cranial nerve surgery, or major cardiac events for carotid revascularization [12]. Thus, careful patient selection and evaluation of the benefit-/risk ratio before carotid artery revascularization are critical points that should be considered by surgeons.

Application of Vascular Ultrasound Before Carotid Artery Revascularization

Several imaging methods, including CDU, CT/CTA, MRI/MRA, and digital subtraction angiography (DSA), are widely used in clinical practice before carotid artery revascularization procedures to help surgeons evaluate patients with carotid artery stenosis-occlusive disease. Among these various imaging modalities, guidelines recommend noninvasive CDU as the preferred initial screening method for patients with carotid artery stenosis [13,14]. In addition, CDU combined with TCCS/TCD can provide information regarding collateral circulation status, especially in patients with severe carotid artery stenosis or occlusion.

CDU

CDU can be used to assess the morphological and hemodynamic alterations in the carotid arteries. The intima-media thickness (IMT) of the common carotid artery (CCA), which can be used as an indicator of cardiovascular risk, should be measured using B-mode ultrasonography. CDU can be used to evaluate the location, size (length and thickness), echo characteristics (isoechoic, hypoechoic, hyperechoic, or with calcification), and shape (regular, irregular, or ulcerated) of the atherosclerotic plaques can be evaluated using CDU. The degrees of stenosis of the carotid artery can be ascertained using hemodynamic parameters derived from Doppler spectrum analysis [15]. More importantly, CDU can assist in differentiating atherosclerotic stenosis from non-atherosclerotic lesions, such as dissection, fibromuscular dysplasia, Takayasu arteritis, embolisms, carotid webs and aneurysms with thrombus formation [16].

Hemodynamic Assessment

The most widely recognized consensus regarding the ultrasound criteria for carotid artery stenosis was published in 2003 [17]. Peak systolic velocity (PSV), end-diastolic velocity (EDV), and the PSV ratio between the internal carotid artery (ICA) and CCA are the primary hemodynamic parameters used to grade the severity of carotid artery stenosis. In some laboratories, the PSV ratio between the stenosis site and distal segment (PSV_{ICA}/PSV_{dist} ratio) to the stenosis is also an important parameter to differentiate between 50%–69% and 70%–99% stenosis [18,19]. Hua et al. reported that the optimal threshold value of PSV_{ICA}/PSV_{dist} ratio for evaluating 50%-69% stenosis was ≥ 1.6, and the cut-off value was ≥ 3.5 for evaluating 70%-99% stenosis, using DSA as a reference criteria [18]. When dealing with a carotid artery with tandem lesions, the PSV ratio is more accurate than the absolute value of the PSV or EDV in diagnosing stenosis severity [19]. In cases of bilateral carotid artery stenosis (one side with severe stenosis and the other with mild or moderate stenosis), Hua et al. recently reported that the degree of stenosis in the contralateral carotid artery may be overestimated when the anterior communicating artery is open, and the veloci-

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ties are increased to compensate for the side affected by severe carotid artery stenosis [20].

Plaque Evaluation

In addition to evaluating the severity of carotid artery stenosis, the evaluation of plaque vulnerability is important as it is associated with patient risk stratification and prognosis, contributes to the selection and design of treatment strategies, and the success, and long-term outcomes of CEA or CAS [21]. In 2003, Naghavi et al. reported the following criteria for identifying vulnerable plaques derived from a study of culprit plaques [22]:

- A thin fibrous cap
- Hemorrhage within the plaque
- A significant lipid core
- Plaque ulceration
- Neovascularity

Recently, Vergallo, R et al. proposed the concept of "high-risk" plaque in the area of cardiovascular system, referring to plaques with an increased propensity to evolve into a clinically relevant thrombosis, and to cause acute coronary syndrome or cardiac death," which include plaque rupture, plaque erosion, and calcified culprit plaque [23]. However, a precise definition of high-risk plaques in the cerebrovascular system needs to be further investigated.

Ultrasound, high-resolution MRI, multidetector-row CT, dual-source CT (DSCT), PET/CT, optical coherence tomography (OCT), intravascular ultrasound (IVUS), and near-infrared spectroscopy-IVUS (NIRS-IVUS) could provide valuable information regarding plaque vulnerability [22,23]. Compared with traditional two-dimensional ultrasound, contrast-enhanced ultrasound (CEUS), three-dimensional ultrasound, and IVUS can provide more information regarding plaque burden, volume, and vulnerability, and have been used in selected patients before CAS or CEA [24-26]. Hypoechoic plaques (with gray-scale median $\leq$ 30.5) and ulcerated carotid plaques have been demonstrated as predictors of postoperative newly ischemic cerebral lesions (NICLs) after CEA [27]. Moreover, the characteristics of carotid plaques, including imaging attributes, cellular makeup, and molecular profiles, are associated with the potential for restenosis following CEA [28]. Although these characteristics of carotid plaques have not been included in the guidelines for the decision or the choice of strategies for carotid artery recanalization, these research results may, to some extent, affect the choice of surgeons in the future.

Compared with traditional CDU, CEUS can provide more information on intraplaque neovascularization and increase the sensitivity and diagnostic accuracy of ulcer plaques; Its accuracy has been demonstrated in histological examinations of CEA specimens [24,29]. The burgeoning field of "molecular imaging", defined as microbubbles conjugated with specific ligands, provides a fresh perspective, even for the initial stage of atherosclerosis. CEUS with microbubbles targeting P-selectin and vascular cell adhesion molecule 1 (VCAM-1), which are important molecules involved in leukocyte trafficking, have been used to identify the inflammatory plaque phenotype, whereas microbubbles coupled to the vascular endothelial growth factor (VEGF) receptor may facilitate the detection of neovascularization [30]. However, molecular imaging using targeted microbubbles remains in the experimental stage and is currently not widely used in clinical practice.

Calcified plaques are another characteristic that must be considered, particularly before carotid artery recanalization. Calcified plaques can be classified into three categories: superficial, basal, and internal calcification [31]. Single- and multicenter studies have demonstrated that calcified plaques, particularly those exhibiting basal calcification, are independent predictors for residual stenosis following CAS [32,33]. Calcified and ulcerated plaques are also independent risk factors for NICL following CAS [34]. The pathological characteristics of various types of plaque calcifications, including size, location, and shape, varies and may generate different plaque biomechanics, which may have different impacts during stent expansion [35,36]. Thus, for patients with calcified plaques, CEA may present as the optimal treatment choice.

In 2024, Plaque-RADS, a standardized cross-modality system for reporting carotid artery plaque composition and morphology was developed to better evaluate carotid artery diseases and predict the risk of cerebrovascular events [37]. The plaque-RADS organizes carotid plaques into four categories based on the degree and combination of vulnerability features as listed in table 1 [37]. Plaques features evaluated by ultrasound are summarized in table 2 [37].

Table 1 Plaque-RADS categories and their imaging findings [37].

Plaque-RADS score	Imaging findings
1	Normal vessel wall
2	MWT < 3 mm
3	MWT ≥ 3 mm or healed ulcerated plaque
3a	LRNC with intact fibrous cap (MWT ≥ 3 mm)
3b	LRNC with thin fibrous cap (MWT ≥ 3 mm)
3c	Healed ulcerated plaque
4	Complicated plaque (irrespective of MWT)
4a	Intraplaque hemorrhage
4b	Ruptured fibrous cap
4c	Intraluminal thrombus

MWT, maximum wall thickness; LRNC, lipid-rich necrotic core.

Table 2 Key plaque features evaluated by ultrasound [37]

Plaque-RADS components	Ultrasound imaging findings
Calcification	Hyperechogenic region with acoustic shadowing
LRNC	Lesion with more than 75% of its area being hypoechoic, or the plaque with gray scale median < 30 this a visible echogenic fibrous cap.
Fibrous cap	Hyperechogenic structure between lumen and bulk of plaque
Plaque ulceration	B-mode: Cavity in the plaque surface, irrespective of size, with a lower surface echogenicity than that of the adjacent plaque surface. CEUS: interruption of the plaque-lumen borders for at least 1x1 mm.
Intraplaque hemorrhage	Currently unsuitable to distinguish large LRNC with a thin fibrous cap from intraplaque hemorrhage.
Intraluminal thrombus	B-mode: Cannot distinguish large LRNC with a thin FC from intraluminal thrombus. CEUS: Hypoechoic filling defect with microbubbles delineating circumferentially the thrombus.

CEUS, contrast enhanced ultrasound; LRNC, lipid-rich necrotic core.

Preoperative Evaluation

Before carotid artery revascularization using CEA, the location of the CCA bifurcation and of culprit plaques, including the presence of unstable plaques at the mid- and proximal-segments of the CCA and their accurate location (i.e., distance to the CCA bifurcation) should be evaluated using CDU. This examination provides significantly more information for surgeons to select revascularization strategies, predict associated risks and increase the success rate of procedures [38].

In addition, combination surgery (CEA combined with Fogarty embolectomy or CEA combined with stenting) may be beneficial for selected patients with symptomatic chronic carotid artery occlusion [39]. CDU can provide the following information, which is helpful for patients selection: First, to differentiate the causes of carotid artery occlusion. Second, to differentiate total or subtotal carotid artery occlusion. Third, to differentiate between simple thrombotic occlusion and thrombotic occlusion secondary to plaque rupture. Fourth, assessment of intraluminal structural changes in carotid artery occlusion. The recanalization success rate in patients with homogenous echo patterns, such as hypo-echoes or iso-echoes, was higher than that in patients with heterogeneous echo patterns. Fifth, the original diameter of the distal ICA ≥ 2 mm and the external carotid artery (ECA)-ICA collateral circulation opening could achieve a much higher success rate of recanalization [39,40].

TCCS/TCD

TCCS and TCD can be used to measure the hemodynamic parameters of intracranial arteries. More importantly, TCCS or TCD can be used to assess the condition of collateral circulation, such as the opening of the anterior communicating artery (ACoA), opening of the posterior communicating artery (PCoA), and collateral circulation of the ECA-ICA before carotid artery revascularization. Collateral circulation evaluated using TCCS or TCD is crucial for stratifying patient risk and selecting treatment strategies for carotid artery revascularization. Insufficient collateral circulation, including severe stenosis or occlusion of the opposite carotid artery, is associated with intra- and postoperative NICLs and hyper-perfusion syndrome during CEA [41,42]. Before CEA, the carotid artery compression test is typically used to evaluate the reduction in the mean velocity of the middle cerebral artery (MCA) to identify whether collateral circulation compensation is sufficient and whether temporary shunting is required [43]. Moreover, we suggest that TCCS/TCD should be used in combination with CDU to increase the diagnostic accuracy for carotid artery stenosis. The advantage of TCCS is that the morphology and blood flow filling of the vessels can be viewed directly, and the Doppler angle can be calibrated in real-time. Thus, its diagnostic accuracy is higher than that of TCD to some extent, particularly for cases of severe stenosis or occlusion of the MCA or vertebral artery-basilar artery (VA-BA). However, the limitation of TCCS is poor penetration, particularly in cases with thicker skulls, which affects the detection rate of intracranial arteries through the temporal window [44,15].

Furthermore, before carotid revascularization, TCD is sometimes used clinically to evaluate the cerebrovascular reactivity (CVR), to predict the potential risk of cerebral blood flow hyper-perfusion after carotid artery revascularization [16]. Dynamic cerebral autoregulation was impaired in patients with moderate and severe carotid artery stenosis and could be restored by CAS or CEA [45,46]. Moreover, impaired dynamic cerebral autoregulation (a lower ipsilateral phase at very low frequency) and impaired CVR ability (breath holding index evaluated by TCD) were predictors for cerebral hyperperfusion syndrome after CEA [45,47].

MES monitoring using TCD may confirm the features of vulnerable plaques in the carotid artery. As mentioned above, ≥ 1 MES during ≥ 1 h TCD monitoring is one of the imaging features for 60-99% stenosis in asymptomatic patients who can consider CEA or CAS [8]. TCD bubble test can identify right-to-left shunts and

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help physicians differentiate the mechanisms of ischemic stroke [48].

Applications of Vascular Ultrasound During Carotid Artery Revascularization

TCD monitoring during CEA and CAS

The roles of TCD during CEA or CAS procedures include the real-time monitoring of velocity alterations in the MCA during different stages of the operation; detecting the number of MES during the operation process; evaluating the decrease in MCA velocities compared with the basal level at the CCA cross- clamping stage during CEA, helping surgeons to determine the necessity of temporal shunting; evaluating the acceleration in MCA velocities at the re-opening of the carotid artery stage during the CEA and helping to predict the risk of hyper-perfusion syndrome during or post-operative processes. TCD monitoring is usually performed during CEA under general anesthesia, which increases the success rate of the surgery and decreases the risk of cerebral ischemia and hemorrhage [38,49].

TCD is used to monitor the MES. The Doppler criteria for MES are as follows: spectral amplitude at least 3db higher than the background noise level, signals with short durations < 300 ms, unidirectional signals, detected in the spectrum, and characteristic acoustic sound [50]. According to the literature, the MES counts are higher during CAS than during CEA. Faraglia et al. reported that the mean MES count during CAS was higher than that during CEA (330 vs. 13.2) and was associated with more DWI-MRI lesions [51]. The MES detected during CAS includes solid (particulate) MES and air MES. Ackerstaff et al. analyzed the TCD monitoring results of 550 patients with CAS and reported that the occurrence of multiple showers of MES (> 5) postdilation following stent placement, as well as particulate macroembolism and significant air embolism, were independently linked to cerebral deficits [52]. MES can occur during different stages of CEA, with most detected during shunting and declamping (i.e., re-opening of the carotid artery) [53]. In CAS, most MES can be detected during the implementation of protective devices and stent deployment [54].

Another role of TCD monitoring during CEA is to determine the necessity for temporary shunts based on the decrease in MCA velocity during the CCA clamping stage. The threshold for the decrease in mean velocity in the MCA to predict the necessity for shunting during clamping has currently no consistent criteria, with a reported range of 40-85% [16,55]. Recently, Chuatrakoon et al. found that routine shunting was linked to a lower risk of stroke-related death within 30 days postoperatively than no shunting. Additionally, patients in the routine shunting group exhibited a decreased stroke rate within 24 h of surgery and a reduced incidence of ipsilateral stroke within 30 days postoperatively compared to those without shunting. Nevertheless, large-scale randomized trials comparing routine and selective shunting are required [56].

TCD is predominantly applied during CEA surgery to monitor MCA velocity with changes in blood pressure, and heart rate, as well as changes in PO_2, PCO_2, or both before and after carotid artery shunting and throughout the entire process. TCD during CEA is also used to predict the risk of hypo- or hyper-perfusion of the cerebral blood flow.

Intraoperative CDU

Intraoperative CDU is sometimes performed during CEA to assess technique adequacy and help surgeons immediately correct significant technique defects. Panneton et al. categorized intraoperative CDU findings into three groups: normal; minor/insignificant lesions, such as moderate plaque/thrombus, small intima flap, stable ECA stenosis, and a PSV in the ICA < 125 cm/s. Hemodynamically significant lesions, such as marked plaque/thrombus or large intima flap dissection, exhibited a PSV ICA > 125 cm/s. Among 155 intraoperative CDU examinations, 14 (9%) showed significant findings that required immediate surgical revision [57]. In 2017, Knappich et al. reported a study of 142,074 CEA cases and found that a modest decrease in the adjusted risk for stroke/mortality was observed when intraoperative CDU was utilized selectively (relative risk 0.74; 95% CI, 0.63-0.88; $P < 0.001$) [58]. Furthermore, a systematic review published in 2022 revealed that intraoperative CDU-detected residual flow abnormalities, if not corrected, were linked to a higher risk of restenosis, ranging from 2.1% to 20% [59].

Application of Vascular Ultrasound After Carotid Artery Revascularization

According to the latest ESVS guidelines, there is currently no evidence to support routine surveillance of individuals undergoing CEA or CAS. However, some patients with an increased risk of restenosis, such as individuals with diabetes, female, smokers, patients with chronic kidney disease or patients who had non-operated carotid artery narrowing > 50%, may benefit from CDU surveillance [8].

CDU follow-up after carotid artery revascularization

Within one week following CEA or CAS, CDU is

conducted to verify the success of the procedure and detect any residual stenosis. Figure 1 presents the ultrasound images of a case with 70-99% ICA stenosis before and after CAS. In addition, CDU can identify possible complications including dissection, pseudoaneurysm, thrombosis, or hematoma [17]. In 2022, Yokoya et al. reported that, among 101 patients with CEA, string-like mobile echodensities (SLMEs) were identified in 8 patients, most of which resolved spontaneously. A few SLMEs were repeatedly observed; however, these lesions did not cause cerebral infarctions or TIA during the follow-up period [60].

In some studies, the rates of residual stenosis or restenosis after CAS were reported to be higher than those after CEA. The EVA-3S study demonstrated that the short-term incidence of carotid restenosis ≥ 50% or occlusion was approximately 2.5 times higher following CAS compared to CEA (12.5% vs. 5.0%; P = 0.02) [61]. Xin et al. published a meta-analysis (27 studies and 20,479 participants) and revealed that CEA was associated with a lower restenosis rate than CAS within 6 months and 1 year. However, there was no distinguishable discrepancy between CAS and CEA when the follow-up period was extended to > 1 year [62]. In CDU, PSV and EDV are important hemodynamic parameters for assessing the severity of restenosis following either CAS or CEA. However, owing to the altered compliance of the stent-artery complex [63,64], the degree of restenosis is overestimated when the velocity thresholds for native arteries are applied, which has been confirmed in VA in-stent restenosis [65]. In addition, the velocity within a stent could be influenced by various types of stents, resulting in distinct effects [66]. Several prior groups have reported CDU criteria for in-stent stenosis after CAS [64,67-69]. However, owing to the comparably limited scope of these studies [64,69] and the application of different re-stenosis grading system [67-69], these published criteria have not been widely used. To date, there is a lack of international consensus on the CDU criteria for assessing the degrees of restenosis in CAS. Pizzolato et al. summarized relevant studies on CDU criteria for restenosis and suggested PSV with a range 300-350 cm/s can be used as a cut-off value for evaluating ≥ 70% restenosis [70]. AbuRahma et al. introduced CDU criteria specifically designed to assess restenosis following CEA with patch closure with the PSV ≥ 274 cm/s as an optimal threshold for evaluating ≥ 70% restenosis [71]. Large-scope studies should be performed to establish the CDU criteria for in-stent stenosis after CAS and CEA. We propose that, after carotid artery revascularization, CDU combined with TCCS/TCD can yield a significantly more accurate evaluation of restenosis severity.

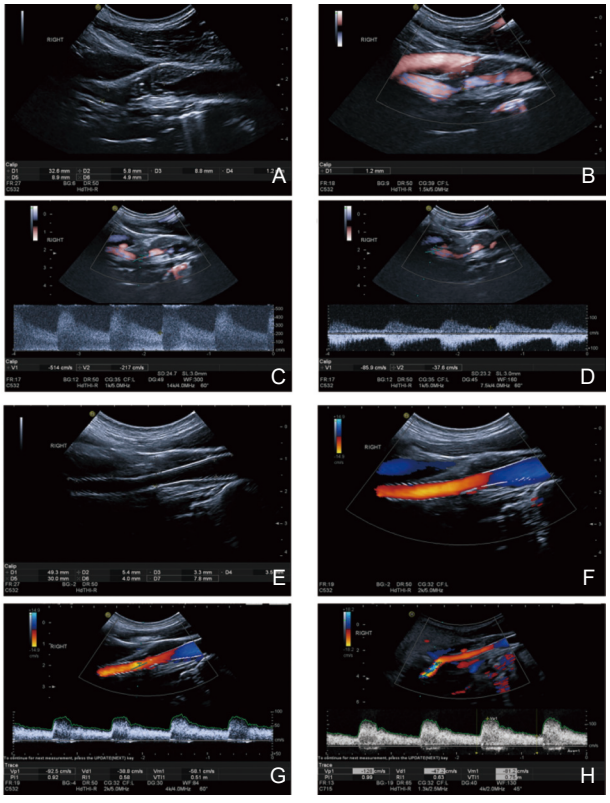


Figure 1 The ultrasound images of a 67-years old male patient with right internal carotid artery (ICA) severe (70-99%) stenosis before and after carotid artery stenting. (A). The 2-D image showed there was a heterogenous plaque at the bulb site of right ICA; (B). The CDFI image showed the local stenosis of ICA with a residual diameter was 1.2 mm; (C). The spectral waveform showed the peak systolic velocity (PSV) at the stenosis site was 514 cm/s and the end diastolic velocity (EDV) was 217 cm/s; (D). The spectral waveform of the distal ICA showed the PSV and EDV were 85.9 cm/s and 37.6 cm/s respectively; (E). The 2-D image of ICA stent with a length of stent 49.3 mm and the diameter of proximal, mid and distal of stent were 5.4 mm, 3.3 mm and 3.5 mm; (F). The CDFI image of the stent showed the blood flow within the stent was sufficient; (G). The spectral waveform showed the PSV and EDV within the stent were 92.5 cm/s and 38.8 cm/s; (H). The spectral waveform showed the PSV and EDV at the distal of ICA were 128 cm/s and 47.2 cm/s.

TCCS/TCD follow-up after carotid artery revascularization

The roles of TCCS/TCD after carotid artery revascularization are as follows. First, to assess the recovery of ipsilateral cerebral blood flow and second, to predict or determine cerebral hyper-perfusion syndrome (CHS).

CHS is a rare but serious clinical syndrome that can be diagnosed using TCD after carotid revascularization. Compromised cerebrovascular autoregulation is crucial in CHS pathology. In addition, damage from free radicals and the breakdown of the baroreceptor reflex have been implicated in the development of CHS [72]. A 1.5- or 2-fold postoperative increase in the mean velocity of the MCA (MCAV) compared with the pre-operative levels (i.e., baseline) may predict CHS [73,74]. In a recent study involving 969 cases of CEA, Li et al. reported an

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ICH incidence of 3.2% and found that the intraoperative percentage increase in MCAV immediately following carotid declamping emerged as a predictor of CHS (OR, 9.840 95% CI, 2.638-36.696]; $P < 0.001$) [75]. In a retrospective review including 4494 individuals, Ogasawara et al. found that 61 (1.4%) patients exhibited postoperative CHS and 27 (0.6%) developed intracranial hemorrhage. The onset of CHS peaked earlier after CAS than after CEA (within 12 h vs. post-operative day). In individuals with CHS following CEA, inadequate post-operative blood pressure management was linked to the occurrence of intracranial hemorrhage [74]. Thus, strict blood pressure control after carotid artery revascularization is important to prevent CHS occurrence [72].

The limitation of this review is that the methods of CDU and TCCS/TCD mainly discussed in this review have been widely used in clinics and we did not involve several methods still in the experimental stage or which has not routinely used in clinics, such as IVUS, computational fluid dynamics techniques based on CTA or CDU imaging and functional TCD in carotid artery revascularization; which might provide more morphology, hemodynamic, and functional parameters for surgeons in the future.

In conclusion, CDU and TCCS/TCD have been widely used during the pre-opwerative, intra-operative, and post- operative periods of carotid artery revascularization, assisting surgeons in diagnosis and risk stratification, reducing surgical complications, and increasing the success rate and long-term outcomes of CAS and CEA (Fig. 2).

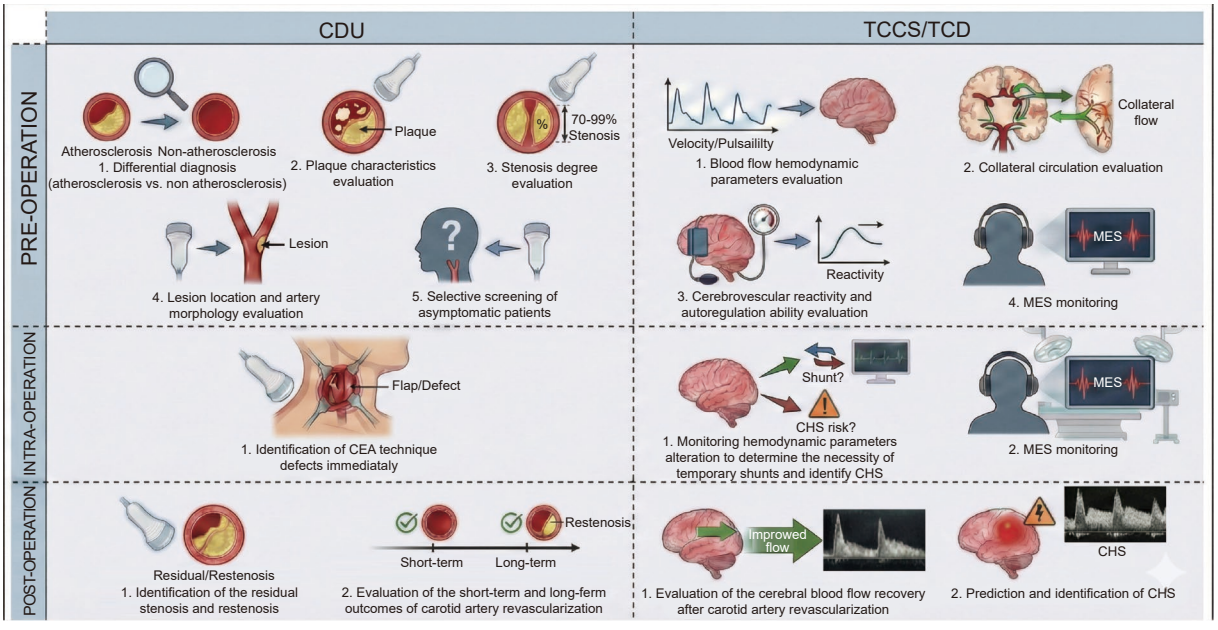


Figure 2 A schematic diagram of application of carotid ultrasound and transcranial color-coded Sonography/transcranial Doppler in carotid artery revascularization. CDU, carotid duplex ultrasound; CHS, cerebral hyperperfusion syndrome; MES, microemboli; TCCS, transcranial color-coded sonography; TCD, transcranial Doppler

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Author Contributions

Conception and design, data curation: Yang Hua and Lingyun Jia; Writing the original draft: Lingyun Jia and Yang Hua. All authors made contributions towards editorial revisions of the manuscript. They have thoroughly read and given their approval to the final version submitted for publication. Additionally, all authors have agreed to take responsibility for every aspect of the work, ensuring that any inquiries regarding the accuracy or integrity of any portion of the work are properly addressed and resolved.

Data Availability

Data sharing is not applicable to this article.

Declarations

Ethical statement and patient consent

Not applicable.

Conflict of interest

The authors had no conflict of interest to declare.

Consent for publication

Not applicable.

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