



ΤΜΗΜΑ ΙΑΤΡΙΚΗΣ
ΣΧΟΛΗ ΕΠΙΣΤΗΜΩΝ ΥΓΕΙΑΣ
ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΙΑΣ
ΜΕΤΑΠΤΥΧΙΑΚΟ ΠΡΟΓΡΑΜΜΑ ΣΠΟΥΔΩΝ
ΥΠΕΡΗΧΟΓΡΑΦΙΚΗ ΛΕΙΤΟΥΡΓΙΚΗ ΑΠΕΙΚΟΝΙΣΗ ΓΙΑ
ΤΗΝ ΠΡΟΛΗΨΗ ΚΑΙ ΔΙΑΓΝΩΣΗ ΤΩΝ ΑΓΓΕΙΑΚΩΝ ΠΑΘΗΣΕΩΝ

Μεταπτυχιακή Διπλωματική Εργασία

***" Η ΧΡΗΣΗ ΤΩΝ ΥΠΕΡΗΧΟΓΡΑΦΙΚΩΝ ΣΚΙΑΓΡΑΦΙΚΩΝ ΜΕΣΩΝ ΣΤΗΝ
ΕΚΤΙΜΗΣΗ ΤΟΥ ΚΑΡΩΤΙΔΙΚΟΥ ΣΥΣΤΗΜΑΤΟΣ"***

ΑΣΛΑΝΙΔΗ ΧΡΙΣΤΙΝΑ

Ειδικευόμενη Ακτινολογίας

Υπεβλήθη για την εκπλήρωση μέρους των
απαιτήσεων για την απόκτηση του
Διπλώματος Μεταπτυχιακών Σπουδών
«Υπερηχογραφική λειτουργική απεικόνιση για
την πρόληψη και διάγνωση των αγγειακών παθήσεων»

Λάρισα, 2023

Επιβλέπων:

Χρήστος Κάρκος, Αναπληρωτής καθηγητής Αγγειοχειρουργικής της Ιατρικής Σχολής του Αριστοτελείου Πανεπιστημίου Θεσσαλονίκης

Τριμελής Εξεταστική Επιτροπή:

1. *Χρήστος Κάρκος, Αναπληρωτής καθηγητής Αγγειοχειρουργικής της Ιατρικής Σχολής του Αριστοτελείου Πανεπιστημίου Θεσσαλονίκης - (Επιβλέπων)*
2. *Αθανασιος Γιαννουκας, Καθηγητής Αγγειοχειρουργικής, Τμήμα Ιατρικής, Πανεπιστήμιο Θεσσαλίας*
3. *Ιωαννης Κακισης, Καθηγητής Αγγειοχειρουργικής, Τμήμα Ιατρικής, ΕΚΠΑ*

Τίτλος εργασίας στα αγγλικά:

"THE ROLE OF CONTRAST ENHANCED ULTRASOUND (CEUS) IN THE EVALUATION OF THE CAROTID SYSTEM"

Περίληψη

Η χρήση των υπερήχου με σκιαγραφική ουσία (CEUS) αποτελεί σήμερα μία πολλά-υποσχόμενη, μη επεμβατική απεικονιστική μέθοδο που, σε συνδυασμό με το έγχρωμο Doppler υπερηχογράφημα, συμπληρώνει την απεικόνιση των αγγειακών παθήσεων. Πολυάριθμες μελέτες έχουν αναδείξει τον ρόλο των CEUS σε πολλαπλά πεδία των υπερήχων των αγγείων συμπεριλαμβανόμενων των καρωτίδων, της κοιλιακής αορτής, των λαγονίων, της πυλαίας και των ηπατικών φλεβών, όπως και των νεφρών και των νεφρικών αρτηριών. Ειδικότερα, όσον αφορά την απεικόνιση των καρωτίδων, τα CEUS μπορούν να χρησιμοποιηθούν για την ακριβέστερη διάγνωση απόφραξης, διαχωρισμού ή και στένωσης, καθώς και για την διαφοροδιάγνωση μιας πλήρους από μία μερική απόφραξη (sub-occlusion). Επιπλέον τα CEUS μπορούν να αναδείξουν με περισσότερη ευαισθησία αλλοιώσεις του καρωτιδικού τοιχώματος όπως έλκη σε αθηροσκληρυντικές αλλοιώσεις και μαλακές -υπόηχες πλάκες. Επιπροσθέτως τα CEUS έχουν την δυνατότητα να προσφέρουν απεικόνιση σε επίπεδο μικροκυκλοφορίας και έτσι να αναδείξουν αυξημένη νεοαγγείωση εντός των αθηροσκληρυντικών πλακών συνεισφέροντας έτσι στον εντοπισμό ευάλωτων αθηρωματικών πλακών με αυξημένη πιθανότητα ρήξης. Τέλος, τα CEUS ενδείκνυνται και για την μετεγχειρητική παρακολούθηση και εκτίμηση της επαναστένωσης μετά από τοποθέτηση ενδοαυλικού stent στην καρωτίδα καθώς και για την εκτίμηση της φλεγμονής του καρωτιδικού τοιχώματος σε έδαφος αρτηρίτιδας.

Σε αυτή την μεταπτυχιακή διπλωματική εργασία θα πραγματοποιηθεί μία συστηματική ανασκόπηση της βιβλιογραφίας μέσω του PubMed σχετικά με την χρήση των σκιαγραφικών υπερήχων και την συμβολή τους στην εκτίμηση παθολογιών του καρωτιδικού συστήματος καθώς και την μετεγχειρητική παρακολούθηση των καρωτίδων μετά από αγγειοπλαστική. Στην ανασκόπηση αυτή συμπεριληφθηκαν συνολικά 23 άρθρα.

Λέξεις-κλειδιά : σκιαγραφικό υπερήχων, καρωτίδες, καρωτιδικό σύστημα, αθηροσκλήρυνση, διαχωρισμός

Abstract

Nowadays, contrast-enhanced ultrasound (CEUS) has evolved into a particularly useful, non-invasive and powerful diagnostic tool in vascular pathology. Many studies have pointed out the role of CEUS in multiple fields of vascular ultrasound such as the carotid arteries, abdominal aorta, iliac arteries, portal vein, hepatic veins, as well as the kidneys and renal arteries and veins. In particular, CEUS in the carotid system can be used for a more accurate diagnosis of occlusion, dissection or stenosis, while it can also be useful in differentiating a complete from a partial occlusion (near-occlusion). In addition, CEUS has the ability to demonstrate carotid wall lesions such as atherosclerotic ulcers and hypoechoic plaques. Furthermore, CEUS is able to offer information about the microcirculation and thus can be able to detect increased neovascularization inside carotid plaques, contributing to the identification of unstable atherosclerotic plaques that carry an increased risk of rupture. Finally, CEUS is also indicated for postoperative monitoring and assessment of restenosis after intraluminal stent placement in the carotid arteries as well as for the identification of carotid wall inflammation in patients with arteritis.

The aim of this thesis is to present and discuss the latest literature regarding the various applications of ultrasound contrast agents in the carotid system and the possibilities they provide, along with the applications of this alternative radiological technique in the daily clinical practice. A systematic review was performed using the literature data base PubMed including 23 full-text articles.

Key-words: contrast-enhanced ultrasound, carotid arteries, carotid system, atherosclerosis, dissection

Table of contents

1. Introduction

1.1 Basic ultrasound principles

1.1.1 Wave terminology

1.1.2 The piezo-electric effect

1.1.3 Interaction between sound and tissue

1.2 Ultrasound contrast agents

1.2.1 Historic overview

1.2.2 Basic characteristics of ultrasound contrast agents

1.2.3 Classification

1.2.3 Adverse reactions and contraindications

1.2.4 Imaging of Ultrasound contrast agents

1.3 Evaluation of carotid artery stenosis and plaque characterization with carotid duplex ultrasonography

2. Materials and Methods

2.1 Search strategy

3. Results

3.1 Study selection

3.1.1 Results of studies included

3.2 Role of contrast-enhanced ultrasound in the grading the degree of carotid stenosis

3.2.1 Differential diagnosis of total occlusion and pre-occlusion stenosis

3.3 Role of contrast-enhanced ultrasound in characterizing carotid atherosclerotic plaques

3.3.1 Carotid plaque ulceration

3.3.2 Carotid plaque enhancement and intraplaque neovascularization

3.4 Other uses

3.4.1 Carotid dissection

3.4.2 Follow up after stenting/endarterectomy

3.4.3 Inflammatory conditions of the carotid artery system

4. Discussion – Future Developments

5. Conclusion

Introduction

1.1 Basic ultrasound principles

Ultrasound (US) is currently one of the most versatile and widely used radiological techniques in the everyday clinical practice. Medical US imaging is based on the transmission and reception of sound waves with frequencies ranging from 2 to 15MHz, although even higher frequencies may be needed in some situations [1].

1.1.1 Wave Terminology

Sound consists of longitudinal vibrations which propagate through a medium as a wave containing compressions (areas of increased pressure) and rarefactions (areas of decreased pressure) [2]. The characteristics of a sound wave can be defined using the following parameters:

1. **Period (T)** The time needed for the particle in the medium to complete on vibrational cycle
2. **Frequency (f)** The number of complete cycles in a unit of time performed by the particles in the medium. Frequency is measured in Hertz (Hz), while high frequencies can be expressed in kHz (1kHz=1000Hz) or MHz (1MHz=1,000,000 Hz)
3. **Wavelength (λ)** The distance of one wave cycle (e.g., between two compressions or two rarefactions)
4. **Velocity (c)** The speed that sound waves move through different mediums. The density and compressibility of a medium strongly affect the velocity of the sound wave. Therefore, propagation velocity differs in each material.

Sound is categorized according to its frequency. In the natural environment, acoustic frequencies vary from less than 1Hz to over 100,000Hz. Human hearing ranges from 20 up to 20,000Hz, while diagnostic US typically ranges from 2 to 15MHz.

1.1.2 The piezo-electric effect

The waves are produced by a transducer consisting of piezo–electric crystals that transforms an electrical signal into an ultrasonic pulse. Therefore, the piezo-electric crystals within the transducer convert electrical energy into mechanical and vice-versa. The transmitted waves propagate through a medium until they encounter reflective or scattered objects, and then return to the transducer as reflected echoes. The transducer crystals convert the reflected echoes back into electrical impulses, which are then further prepared in order to build the US image that is visualized on the screen.

1.1.3 Interaction between sound and tissue

As sound moves through different tissues within the body, various factors result in energy loss and therefore a reduction in amplitude and intensity. Attenuation is defined as this loss of energy and it is determined by the medium involved, the distance traveled and the frequency of the beam. The attenuation of sound energy is significant since it affects how deep the tissue from which useful information can be collected can be. There are four main processes contributing to the attenuation of sound, which are: reflection, refraction, absorption and scattering [3].

Reflection

Reflection appears at the junction between tissues with a difference in their acoustic impedance (Z). A simpler definition of acoustic impedance is $Z = \rho c$, where ρ is the density of the tissue in kg/m and c is the speed of sound in m/s [3]. The amount of reflected sound increases and the amount of transmitted sound decreases accordingly as the density difference increases. The sound is entirely reflected if the tissues are very different regarding their density, which results in total acoustic shadowing. Bones, calculi (gallbladder, kidneys etc.) and air bubbles (gastrointestinal system) all exhibit acoustic shadowing. If variation between the tissues does not exist then echoes will not be produced. Blood, urine, bile, ascites, etc. are homogeneous fluids that are depicted on US as echo-free structures.

Refraction

Refraction is the alteration of the pathway of a sound wave, when it passes through tissues with different propagation velocities, when the angle of incidence to an interface is not 90°. Refraction is significant because it can cause misregistration of a structure in an US image.

Absorption

Absorption is the shifting of the energy of a sound wave into the material in which the sound is traveling. Absorption produces a heating effect and it increases with the increase in the frequency.

Scattering

Scattering appears when a sound wave travels through an area with a different acoustic impedance than the tissue around it, with individual dimensions smaller than the wavelength of the sound wave. The echoes of these interfaces are scattered in all areas. Such structures are known as 'diffuse reflectors' and represent the echoes that create the distinctive echo patterns that solid organs and tissues display.

1.2 Ultrasound Contrast Agent

1.2.1 Historic overview

The use of CEUS begun in the last years of 1960s after discovering that the administration of agitated saline causes a distinguishable change in the signal amid US examination [4]. Contrast enhancement occurred due to the compressible gas center of saline bubbles, allowing the bubbles to backscatter the applied US wave. The high surface tension of those first bubbles caused instability. In the decade of 1970s, the area of ultrasound contrast agents (USCA) developed further and it primarily involved applications in cardiology. Nonetheless the full potential of CEUS could still not be investigated, due to the insufficient lifetime and non-defined size of the bubbles [5]. Circulation time was efficaciously evolved by substituting air for perfluorinated gases that have low solubility in water, such as sulfur hexafluoride [6], perfluoropropane [7] or perfluorobutane [8], resulting in sufficient lifetime enough for clinical use. More than 20 years were needed in order to create the first stable and commercially accessible ultrasound contrast agent, Albunex®, a microsphere covered with albumin and filled with air. [9]. In the following years, persistence and clinical effectiveness of USCA have been improved and micro-bubbles targeting specific surface molecules expressed in pathologic conditions have been developed.

1.2.2 Basic characteristics of Ultrasound Contrast Agents

USCA can be defined as exogenic substances which can be injected either intravenously or inside a cavity. USCA increase the backscattered signal intensity and thus improve the Doppler analysis and highlight the details of the anatomical structures [10]. The majority of USCA in use are composed of microbubbles (typically 3µm in diameter) of gas, such as sulphur hexafluoride, perfluorohexane, air or nitrogen [10,11]. Air was the gas of choice in the earlier USCA as well as in some of the latest ones. However, inert gases with higher molecular weight may be superior due to the fact that they have a low solubility in blood and thus can have a longer half-life [5]. Microbubbles are surrounded by a shell in order to improve the stability in the bloodstream and create a standardized size. The shell consists of stabilizing materials such as phospholipids, albumen or galactose [12, 13]. Microbubbles have the same osmotic pressure as the human plasma and are removed from the body through the lungs [10].

1.2.3 Classification

USCA can be categorized into two types depending on the type of gas that is used inside the microbubbles. First- generation contrast agents, launched in 1996, contained microbubbles of air within thin shells consisting of protein, polymer or phospholipids [5, 14]. However, air presents high solubility in blood and thus first-generation contrast agents had a very short circulation time during exposure to the acoustic pressure of the ultrasound field [14]. Therefore, their presence in the blood was limited and only intermittent scanning was feasible. In order to improve the lifespan of the microbubbles, air was replaced by inert gases with low diffusion coefficients and low solubility in blood [15]. Gases that were mostly used for this purpose were sulfur hexafluoride and perfluorobutane and thereby second-generation contrast agents were introduced [14,15]. Inert gases used in second-generation contrast agents were also surrounded by a shell consisting of lipid, proteins or biopolymers in order to control their size distribution and achieve firmness [14]. A partial list depicting first and second generation USCA is demonstrated in Table 1.

Table 1 Ultrasound contrast media: first and second generation in comparison

	First generation	Second generation
Ultrasound contrast media	Levovist (Schering AG, Berlin, Germany)	SonoVue (Bracco Imaging Spa, Collioretto Giacosa (TO), Italy)
Structural characteristics	Air microbubbles with casing of galactose and palmitic acid	Sulfur hexafluoride microbubbles stabilised by membrane phospholipid
Physical properties	Stimulated acoustic emission	Nonlinear oscillation

Table 1. Παγγι: (Esposito F, Di Serafino M, Sgambati P et al. Ultrasound Contrast Media in Paediatric Patients: Is It an Off-Label Use? Regulatory Requirements and Radiologist's Liability. Radiol med. 2011;117(1):148-59.)

1.2.4 Adverse reactions and Contraindications

In general, USCA are quite safe carrying a low rate of complications. USCA that have been approved for clinical practice are all microbubble-based (Table 2). Unlike iodinated contrast agents, microbubbles do not have renal toxicity and do not interact with the thyroid [16]. The adverse effects are uncommon and of mild intensity and usually do not require any treatment. Most common side effects reported in clinical trials include mild nausea or emesis, flushing, pruritus, mild urticaria, injection site pain and cephalalgia. [12, 17, 18]. More serious adverse reactions of USCA are quite rare, especially when comparing to CT and MRI contrast agents [19]. In a study of 23,188 cases of USCA the incidence of serious side effects was only 0,0086% (n=2) while the total cases with an adverse effect were 29 [20]. Although very rare, temporally related fatal adverse events have been recorded in the literature in patients with coexistent coronary artery disease

[21, 22]. Following these events, in 2007 the US Food and Drug Administration (FDA) released a black box warning for Definity and Optison including contraindications such as aggravated or unstable heart failure, acute myocardial infarction, acute coronary syndrome, severe ventricular arrhythmia or high risk for arrhythmia and pulmonary hypertension [23]. It also required a 30-minute monitoring period after the injection of USCA. Since then, many investigators started publishing studies about the safety and improved efficacy of USCA. The low incidence of severe complications has remained stable in these following studies. At present, hypersensitivity to any of the contrast agents is listed as the only contraindication in Lumason, Definity and Optison [24, 25]. However, all USCA still have a warning of the rare event of severe cardiopulmonary events. Despite the low incidence of adverse effects, USCA should always be used with caution along with readily available resuscitative equipment and experienced professionals on site.

Table 2. Clinically approved ultrasound contrast agents.

Name	First approved for clinical use	Shell material	Gas	Application (examples)	Producer/distributor	Countries
Optison	1998	Cross-linked serum albumin	Octafluoropropane	Left ventricular opacification, endocardial border delineation, Doppler	GE healthcare, Buckinghamshire, UK	USA, Europe
Sonazoid	2006	Hydrogenated egg yolk phosphatidyl serine (HEPS)	Perfluorobutane	Myocardial perfusion, liver imaging	GE healthcare, Buckinghamshire, UK/ Daiichi Sankyo, Tokyo, Japan	Japan, South Korea, Norway, Taiwan, China
Lumason/SonoVue	2001/2014	Phospholipid	Sulphur hexafluoride	Left ventricular opacification, microvascular enhancement (liver and breast lesion detection)	Bracco Diagnostics Inc., Monroe Township, NJ, USA/Bracco Imaging S.p.A., Colleretto Giacosa, Italy	USA, Europe, China, Brazil
Definity/Luminy	2001/2006	Phospholipid	Octafluoropropane	Echocardiography, liver/kidney imaging (Canada)	Lantheus Medical Imaging Inc, North Billerica, MA, USA	North America, Europe
Imagent/Imavist	2002, withdrawn	Phospholipid	Perfluorohexane, Nitrogen	Echocardiography, heart perfusion, tumor/blood flow anomalies	Schering AG, Berlin, DE	USA
Echovist	1991, withdrawn	Galactose microparticles	Air	Right heart imaging	Schering AG, Berlin, DE	Germany, UK
Levovist	1995, withdrawn	Galactose microparticles, palmitic acid	Air	Whole heart imaging, Doppler imaging	Schering AG, Berlin, DE	Canada, Europe, China, Japan
Albunex	1993, withdrawn	Sonicated serum albumin	Air	Transpulmonary imaging	Molecular Biosystems Inc., San Diego, CA, USA	Japan, USA

Adapted from Paefgen et al. 2015.

Table 2.

Πηγή:Frinking P, Segers T, Luan Y, Tranquart F. Three Decades of Ultrasound Contrast Agents: A Review of the Past, Present and Future Improvements. *Ultrasound Med Biol.* 2020 Apr;46(4):892-908.

1.2.5 Imaging of ultrasound contrast agents

Microbubbles act by enhancing the echoes, causing the echo intensity to increase depending on the difference in the acoustic impedance between the blood and the microbubbles [5]. The difference in the acoustic impedance at this interface is increased

which means that all of the incident sound is reflected, even though not all of it will reach back the transducer. However, even though the acoustic reflection of the wave is almost complete, it would not be enough in order to retain a strong enhancement due to the small dimensions and sparsity of the microbubbles in the blood. By a fortunate coincidence, microbubbles display a high echogenicity, which originates from the fact that they vibrate very strongly at the frequencies that are used for diagnostic US exams [11]. It is due to this fact that microbubbles can be extremely more reflective than human tissues. If microbubbles were the same size but rigid which would result in a loss of the ability to resonate, they would be a lot less echogenic [26]. Of course, microbubbles must retain small dimensions to be able to travel through the capillaries ($7.5\mu\text{m}$) and the critical frequency depends on the diameter of the bubbles. Once again, the fortunate coincidence constitutes on the fact that the frequency in which microbubbles $1\text{-}7\mu\text{m}$ in diameter resonate ranges within $2\text{-}15\text{MHz}$, which is the frequencies that are used in US [5].

1.3 Evaluation of carotid artery stenosis and plaque morphology with carotid duplex ultrasonography

Carotid Duplex ultrasound (CDU) is a widely used imaging technique for estimating the degree of carotid artery stenosis as well as measuring the intima-media thickness and aiding in the characterization of the plaque morphology.

Carotid artery stenosis is an important risk factor for ischemic events, accounting for 10-20% of strokes or transient ischemic attacks (TIA) [27]. The standard CDU combines grayscale B-mode imaging along with Colour Doppler and pulsed wave Doppler imaging. The degree of stenosis is measured by evaluating the waveform at the narrowest site of the lumen. Recommended measurements include the peak-systolic (PSV) and end-diastolic velocity (EDV) at the distal part of the common carotid artery (CCA) and the internal carotid artery (ICA) [28]. Many criteria have been used for the evaluation of the degree of the ICA stenosis. The most widely applied are those of The Society of Radiologists in Ultrasound (SRU) which are shown in Table 3 [28].

Degree of Stenosis (%)	Primary Parameters		Additional Parameters	
	ICA PSV (cm/sec)	Plaque Estimate (%)*	ICA/CCA PSV Ratio	ICA EDV (cm/sec)
Normal	<125	None	<2.0	<40
<50	<125	<50	<2.0	<40
50–69	125–230	≥50	2.0–4.0	40–100
≥70 but less than near occlusion	>230	≥50	>4.0	>100
Near occlusion	High, low, or undetectable	Visible	Variable	Variable
Total occlusion	Undetectable	Visible, no detectable lumen	Not applicable	Not applicable

* Plaque estimate (diameter reduction) with gray-scale and color Doppler US.

Table 3. Πηγή: SRU- criteria for estimating the degree of ICA stenosis [28]

Intima-media thickness (IMT), which is measured on grayscale B-mode ultrasound, has been established as a biomarker for atherosclerosis. IMT should be measured at the distal part of the CCA, in a segment without a focal lesion [29]. A measurement >1mm is taken as abnormal.

A carotid artery plaque is defined as a focal thickening of the vessel wall that extends into the lumen >1,5mm or has a thickness exceeding the surrounding IMT by >50% [30]. The characteristics of the plaque including the echogenicity, location, thickness, surface and the presence of ulceration or possible stenosis are crucial for predicting upcoming cardiovascular events [29]. The plaque echodensity can be classified from 1 to 4, from echolucent to almost entirely echolucent, almost entirely echogenic and echogenic [29]. Plaque echolucency is a strong marker of plaque instability. The plaque surface could be described as smooth, irregular or ulcerated. Patients with ulcerated carotid plaques carry a high risk for cerebrovascular events. Large plaque ulcerations can be demonstrated as craters inside the plaque with reversed or stagnated flow. However, CDU has a low sensitivity for the identification of carotid plaque ulceration while it can also be operator dependent. The diagnostic accuracy of CDU ranges from 30 to 80% when compared to histopathological specimens [31].

Materials and Methods

2.1 Search strategy

This systematic review included reports regarding the use of CEUS in the assessment of carotid artery pathology. Data were collected from the literature data base PubMed. The

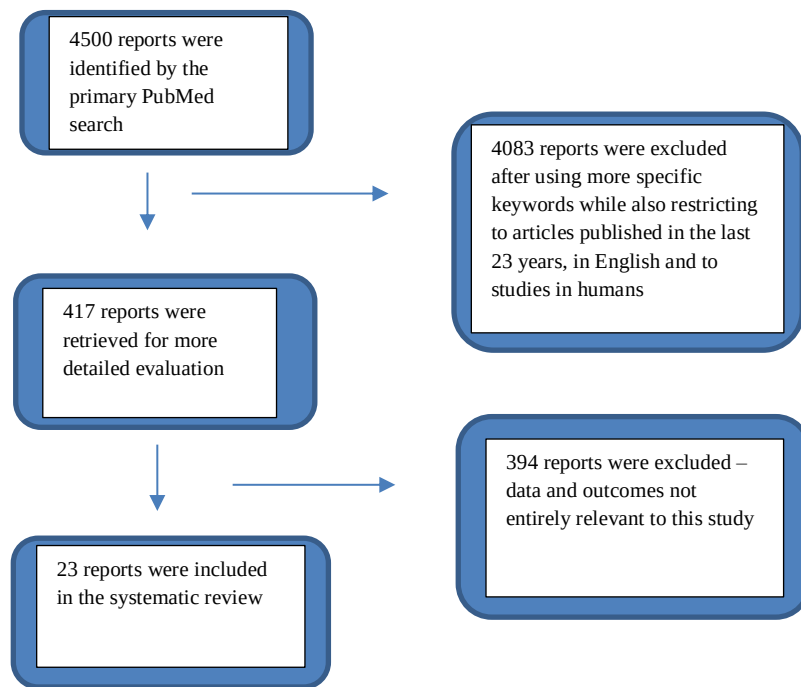
keywords ultrasound contrast agents, carotid system, carotid plaques, Intima-media thickness, contrast-enhanced ultrasound, CEUS, carotid, atherosclerosis, occlusion and stenosis, as well as combinations of the above, were used as appropriate. The search was limited to articles published in English and to studies examining humans.

Results

3.1 Study selection

Searching PubMed with the aforementioned key-words yielded numerous records (up to 4500). A more specific search was conducted using the keywords that were more closely associated with the title of the thesis while also restricting to articles published in the last 23 years, in English and to studies in humans. For example, using the key-words ‘contrast-enhanced ultrasound’ and ‘carotid’. This time searching PubMed yielded 417 results, published in the last 23 years. Abstracts were reviewed in order to detect relevant information which were then examined in detail in the full-text. References of the papers were assessed in order to find further studies in the literature. After elimination of all articles not entirely relevant to the topic of our search, the final selection included 23 articles found to be closely related to the applications of CEUS in the carotid system (Figure 1).

Figure 1. Flowchart demonstrating the pathway that was followed for the selection of the final reports.



3.1.1 Results of studies included

Through this review of the literature, articles about the applications of contrast-enhanced ultrasound in the carotid system over the last decade were reviewed. The majority of the published articles in the field of the applications of CEUS in the carotid system were about atherosclerotic plaque and intraplaque neovascularization as well as carotid artery stenosis. There was also a significant number of studies investigating the role of CEUS in differentiating between occlusion and pre-occlusion stenosis of the carotid artery. A smaller number of articles discussed the application of CEUS in evaluating disease activity in Takayasu disease as well as identifying carotid artery dissection. One published article about the role of CEUS in the follow-up of carotid stenting and endarterectomy was included in the study. The results are demonstrated in table 4.

Table 4. Summary of the selected articles on the applications of CEUS in the carotid system.

Author(year)	Study subject	No. of patients	Population/inclusion criteria	Results/Conclusion
J M Baud (2020) ^[32]	Carotid plaque instability	33	Stroke<10days, carotid plaque thickness $\geq 2,5\text{mm}$	Contrast enhancement of the carotid plaque ipsilateral to a recent ischemic event in 34% of patients
Clevert DA (2011) ^[33]	Carotid plaque instability	33	Patients with carotid atherosclerotic plaques	CEUS allows the dynamic evaluation of neovascularization within carotid plaques
Kono Y (2004) ^[34]	Degree of carotid artery stenosis	20	ICA stenosis $\geq 70\%$	CEUS provides accurate depiction of carotid stenoses, plaques and ulcerations
A Holden (2000) ^[35]	Degree of carotid artery stenosis	28	Patients with equivocal carotid duplex ultrasound	CEUS improved diagnostic confidence in equivocal carotid ultrasound exams

CJ Hammond (2008) ^[36]	Degree of carotid artery stenosis	31	carotid occlusion on conventional ultrasound and with recent ipsilateral hemispheric TIAs	CEUS superior to 2D-TOF MRA in identifying carotid occlusion
Venture CA (2015) ^[37]	Degree of carotid artery stenosis	72	Suspected ICA occlusion	CEUS is as effective as DSA in differentiating between a total occlusion and a pre-occlusion stenosis of the ICA
Van den Oord SC (2013) ^[38]	Carotid plaque instability	69	Asymptomatic patients with heterozygous familial hypercholesterolemia	Quantification of intraplaque neovascularization with CEUS is feasible
Xiong Li (2009) ^[39]	Carotid plaque instability	104	At least one atherosclerotic plaque thicker than 2mm	Symptomatic patients had a stronger intraplaque enhancement than asymptomatic - CEUS can be used for plaque risk stratification
Ten Kate GL (2013) ^[40]	Carotid plaque instability	20	Symptomatic stenosis of ICA	CEUS is an effective method for identifying carotid plaque ulceration
Varetto G (2012) ^[41]	Carotid plaque instability	51	Patients with indication for internal carotid endarterectomy	CEUS is as significant tool for the stratification of carotid plaque instability
Macioch JE (2004) ^[42]	IMT measurement	26	Patients referred for standard carotid ultrasound	CEUS is superior to conventional ultrasound in estimating CCA IMT
HFJ Muller (2014) ^[43]	Intraplaque neovascularization	33	Symptomatic stenosis >50%, Asymptomatic stenosis >60%	Visual analysis of neo-vascularization with CEUS is accurate
Coli S (2008) ^[44]	Intraplaque neovascularization	32	At least 1 atherosclerotic carotid stenosis >30%	CEUS provides valuable findings for plaque risk stratification and for evaluating the response to the treatment of atherosclerosis
Y Zhou (2013) ^[45]	Intraplaque neovascularization	46	Carotid stenosis >50%	Intraplaque neovascularization detected with CEUS is associated with the presence

				of microembolic signals -CEUS may detect high risk plaques
GL Faggioli (2011) ^[46]	Intraplaque neovascularization	22	Symptomatic or asymptomatic carotid artery stenosis >70%	CEUS can be used as a tool for identifying vulnerable plaques
Hoogi A (2011) ^[47]	Intraplaque neovascularization	27	Patients with indication for internal carotid endarterectomy	Quantification of intraplaque neovascularization detected with CEUS is a promising tool for assessing the vulnerability of the plaque
MF Giannoni (2009) ^[48]	Intraplaque neovascularization	77	Patients with indication for internal carotid endarterectomy	CEUS allows the detection of microvessels with neovascularization within a carotid plaque
Owen DR (2010) ^[49]	Carotid plaque inflammation	37	Atherosclerotic plaque causing a stenosis >30%	Late-phase enhancement of the carotid plaque was higher in the symptomatic group of patients-CEUS can be used as a tool for identifying inflammation and for assessing risk stratification of carotid plaques
LY Ma (2019) ^[50]	Takayasu arteritis	84	Active Takayasu disease	CEUS can be used as an alternative tool in assessing disease activity in Takayasu patients
Magnumi M (2011) ^[51]	Takayasu arteritis	1	-	CEUS allows the detection of inflammation-driven hyperaemia and neovascularization, a marker of disease activity
AFL Schinkel (2014) ^[52]	Takayasu arteritis	7	Patients with established large-vessel vasculitis	CEUS improves the visualization of the lumen border and allows the evaluation of wall vascularization,

				a potential marker of disease activity
Clevert DA (2011) ^[53]	Restenosis after carotid stenting	30	Follow-up after carotid artery stenting	CEUS is a valuable tool for detecting in-stent restenosis after carotid stenting
Li ZJ (2015) ^[54]	Carotid artery dissection	1	-	CEUS improves the sensitivity of conventional US in the detection of carotid dissection

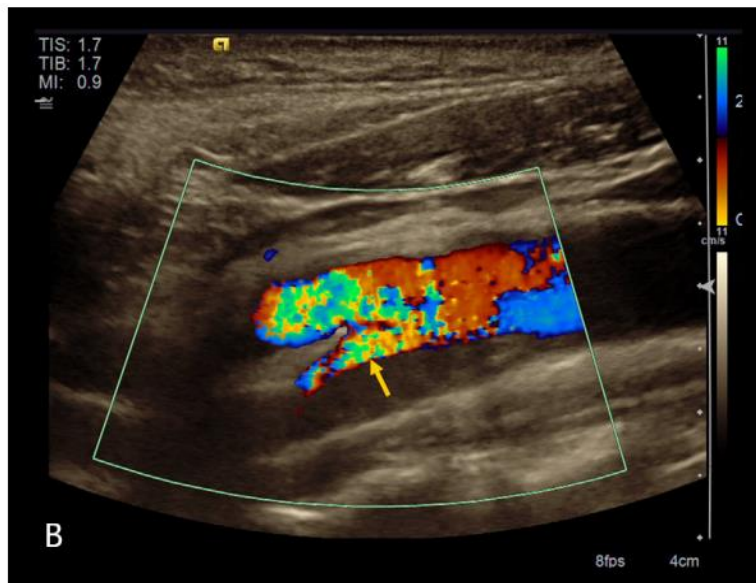
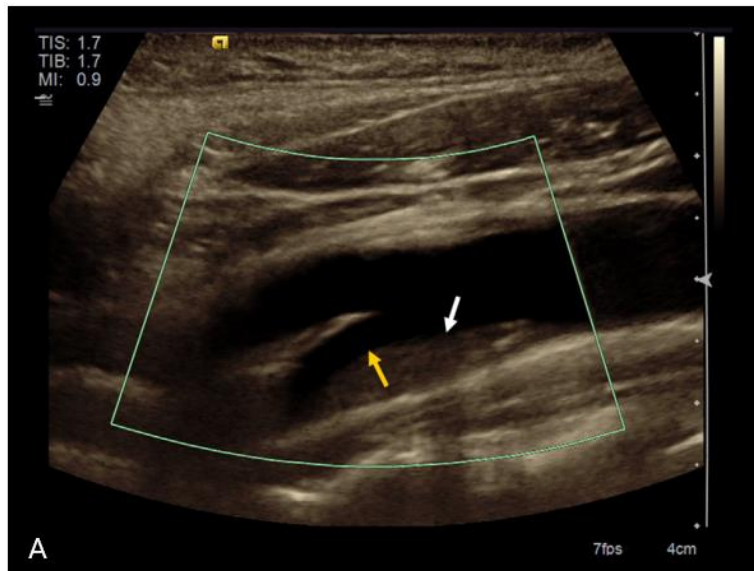
3.2 The role of CEUS in the grading the degree of carotid stenosis

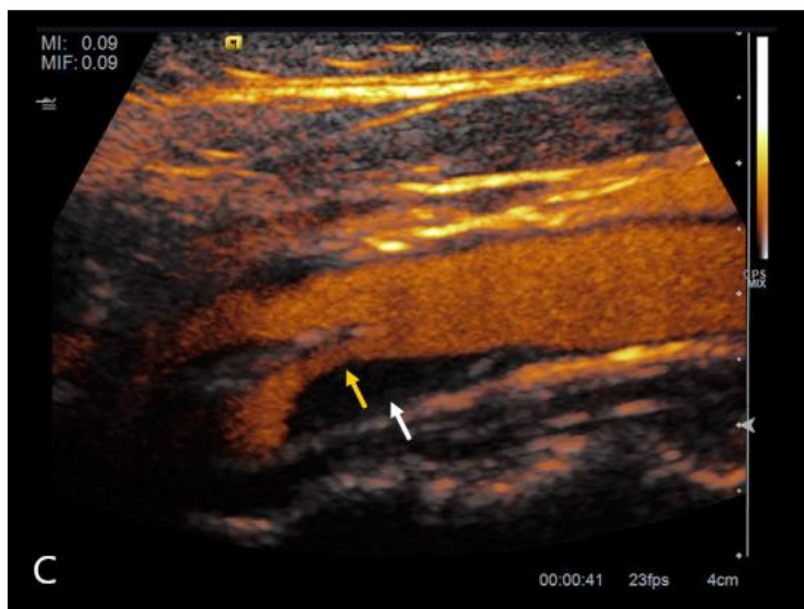
CDU is essential both for screening and diagnostic evaluation of carotid disease and it can be a great imaging method for demonstrating the blood flow inside the vessel and identifying segments with stenosis. However, its value is significantly limited by pitfalls which can lead to a misdiagnosis. Firstly, CDU can be insufficient in the assessment of low-velocity blood flow, particularly in cases of severe carotid stenosis [55]. Secondly, in cases of heterolateral carotid artery stenosis, the PSV can be falsely increased without an actual hemodynamically important stenosis [29]. Moreover, vessels with an oblique direction may demonstrate poor filling of the vascular lumen, due to the Doppler angle dependence [55]. Finally, the aliasing artefact which is related with pulse repetition frequency is another pitfall of CDU that lowers the quality of flow visualization [55].

The introduction of CEUS aims to overcome these limitations. Sirlin [56] and Kono [34] were among the first to explore the possible applications of CEUS in the assessment of carotid stenosis, proving that it can be superior to Color-Doppler in terms of accurately grading a stenosis. CEUS offers simultaneous depiction of the flow in the pre-, intra- and post-stenotic part of the lumen, even in elongated plaques and stenotic segments [57, 58]. This is also possible because the high-velocity and low-velocity flow areas are detected simultaneously without aliasing and blooming artefacts and without an angle dependence. CEUS has been proved to enhance and surpass the performance of CDU by accurately delineating the plaque surface and highlighting wall irregularities thus resulting in an accurate visualization of vessel stenosis (Figure 2).

Figure 2. (A) 69-year-old female patient with recent ischemic event. B-mode ultrasound reveals a significant ICA stenosis (yellow arrow) with soft plaque (white arrow). (B)

Colour Doppler Ultrasound demonstrates the high-grade stenosis of the ICA. However, the full extent of the stenotic segment is not clearly visualized. (C) CEUS visualizes the flow inside the stenosis (yellow arrow) without the aliasing artefact and clearly demonstrates the residual stenotic segment of the lumen as well as the extent of the stenosis and the plaque.



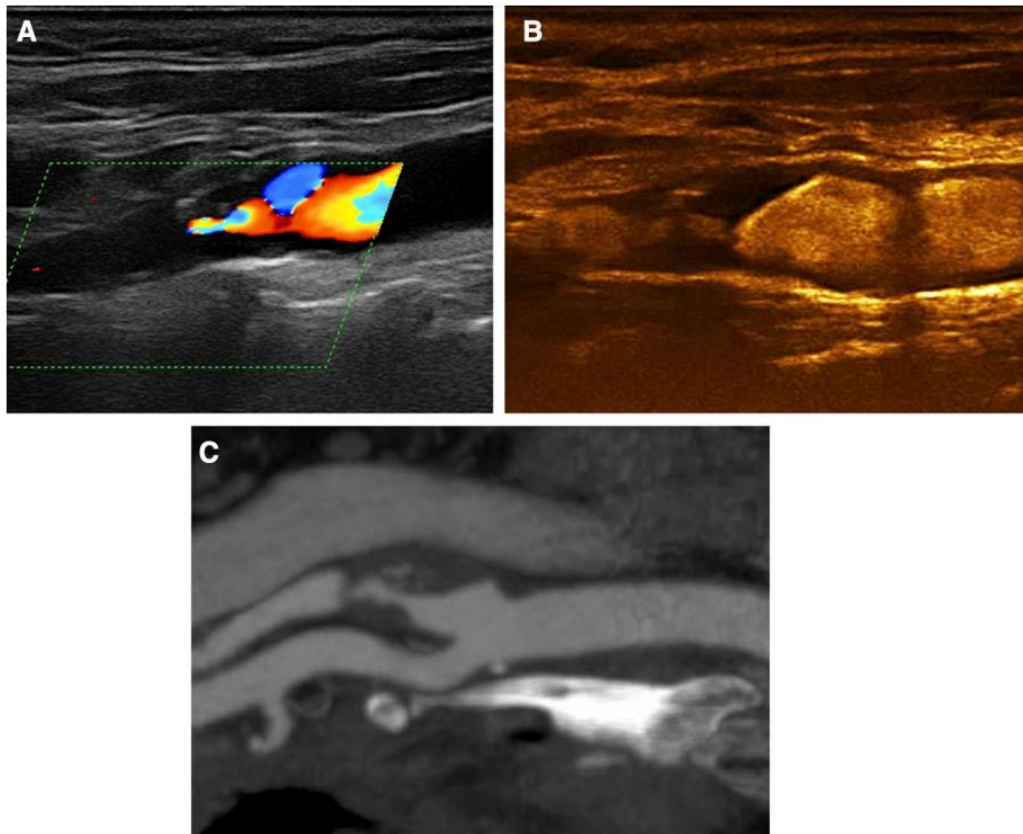


Πηγή: Clevert DA, Helck A, Paprottka PM, et al: Contrast-enhanced ultrasound imaging of the carotid artery. Radiologe 51 (6):483-489, 2011

3.2.1 Differential diagnosis of total occlusion and near-occlusive stenosis

ICA stenosis is the leading risk factor for ischemic strokes, with the risk dictated by the degree of the stenosis. Norris et al [59] demonstrated that patients with an asymptomatic carotid stenosis of <75% had an annual risk of 1,3% while patients with a stenosis more than 75% had an annual risk for TIAs and strokes combined of 10,5%. Although ICA stenosis is the main cause of ischemic episodes, total ICA occlusion rarely leads to ischemic events. Therefore, total ICA occlusion does not require intervention. On the other hand, high-grade stenosis of ICA should be treated surgically or interventionally order to prevent a possible embolization leading to an ischemic event [58]. Thus, differentiating a near-occlusion stenosis (at least 90%) of the ICA from a total ICA occlusion is crucial due to the different treatment pathways. Near occlusion of the ICA is a relatively rare clinical entity with an incidence ranging from 0,5% to 2% [60]. Digital subtractive angiography (DSA) is the gold standard for the evaluation of the degree of the stenosis of the ICA but it is an invasive method associated with post-procedure complications [55]. CTA and MRA are non-interventional methods that also offer an alternative pathway for the diagnosis of carotid occlusion. Colour Doppler Ultrasound is effective in grading the degree of the stenosis but it can lead to a misdiagnose in cases of near-occlusion ICA stenosis with a slow flow. CEUS has been proved to be accurate in differentiating between occlusion and near-occlusion of the ICA and has been proved even more sensitive than time-of-flight (TOF) MRI and equal to contrast-enhanced MRA. It has been concluded that CEUS can replace DSA in the assessment of cases with a suspected near-occlusion stenosis of the ICA [35, 36]. (Figure 3)

Figure 3. A 66-year-old male patient without any symptoms presented with an irregular ICA plaque. (A) Colour Doppler ultrasound demonstrated atherosclerotic lesions in the origin of ICA with absence of blood flow distally, arousing suspicion of total occlusion (B) CEUS depicted the presence of flow inside a segment with a high-grade stenosis due to plaques. (C) CTA revealed the same findings as CEUS.



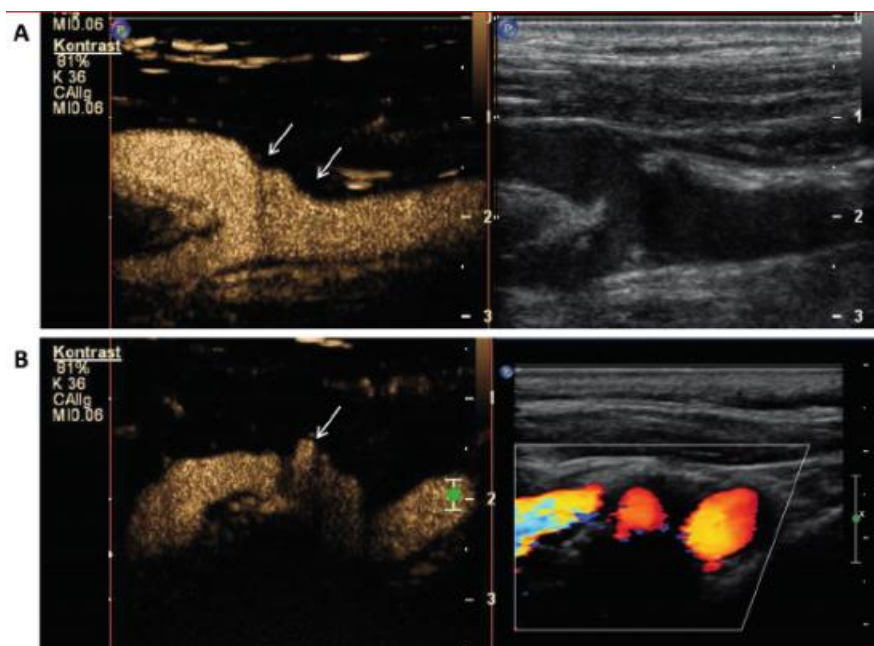
Πηγή:Rafailidis V, Charitanti A, Tegos T, Destanis E, Chrysosgonidis I. Contrast-enhanced ultrasound of the carotid system: a review of the current literature. *J Ultrasound*. 2017 Feb 9;20(2):97-109

3.3 Role of CEUS in characterizing carotid atherosclerotic plaques

As mentioned above, the most widely accepted predictor of the risk of an ischemic event is the degree of the carotid stenosis. Even so, it is becoming increasingly obvious over the last few years that additional factors besides the degree of the stenosis also correlate with the occurrence of stroke. Plaque morphology and composition have been considered to have a great impact on the pathogenesis of a stroke [61]. Atherosclerotic plaques may transform into unstable plaques, also characterized as ‘vulnerable’, which are more prone to rupture. These vulnerable plaques constitute a topic of great clinical significance, as numerous studies have demonstrated a strong association with the occurrence of neurological sequelae such as TIAs or cerebrovascular ischemic events. Due to inherent technical artefacts and limitations the accuracy of diagnosing unstable plaques by

conventional ultrasound techniques may be occasionally limited. The introduction of CEUS during the last years has offered a solution to these limitations, yielding additional information compared to conventional ultrasound by allowing a better depiction of the luminal borders and a more precise delineation of plaque morphology and surface (Figure 4A). In a study by van den Oord et al [38] investigating asymptomatic patients with cardiovascular risk factors, it was revealed that CEUS accurately detected subclinical atherosclerosis by identifying plaques that were missed on CDU due to their low echogenicity. Intraplaque neovascularization, plaque ulceration and low echogenicity all contribute to the instability of the plaque [63, 64, 65]. Echolucent carotid artery plaques which represent a high content of lipids or an intraplaque hemorrhage have been correlated with an elevated risk of cerebrovascular disease, regardless of the degree of carotid stenosis [66].

Figure 4. CEUS allows for a better depiction of vessel wall irregularities. (A) Echolucent and echogenic plaques at the carotid bulb – the echolucent plaque is not identified as clearly on B-mode ultrasound (arrows) (B) CEUS revealing an ulcerated plaque (arrow) at the origin of the ICA that was not depicted on Colour Doppler Ultrasound.



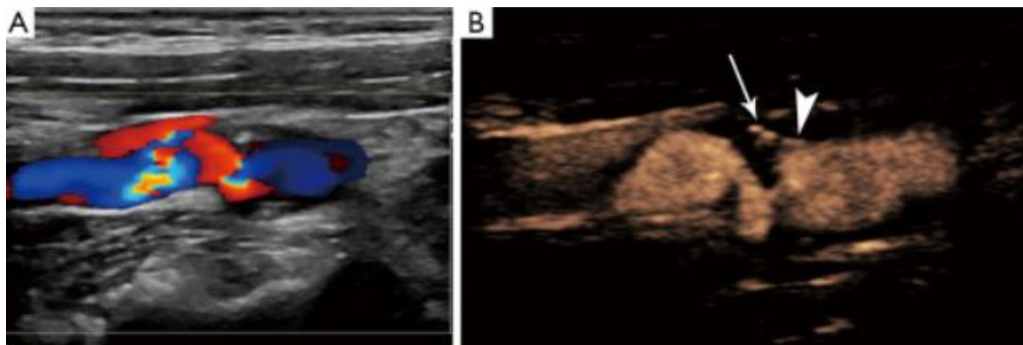
Πηγή: Staub D, Partovi S, Imfeld S, Uthoff H, Baldi T, Aschwanden M, Jaeger K. Novel applications of contrast-enhanced ultrasound imaging in vascular medicine. *Vasa*. 2013 Jan;42(1):17-31.

3.3.1 Carotid plaque ulceration

Numerous imaging methods have been developed for the detection patient with carotid plaques that are in a risk of rupture. Early detection of these patient could prevent clinical complications such as TIAs and stroke. Plaque ulceration has been strongly associated

with atherosclerotic events. B-mode and Colour Doppler ultrasound have a high specificity but lack sensitivity for the detection of ulcerated plaques. Several studies have proved the superiority of CEUS compared to CDU for the identification of plaque ulceration [55, 40]. Ulceration constitutes the most dangerous plaque surface irregularity and it is defined as focal gap in the border between the plaque and the lumen that is at least 1mm or 2mm in depth according to different studies [40, 67]. Each ulcer is characterized by a neck and base that differ in their dimensions and shape [68]. The first criteria for the diagnosis of an ulcerated plaque, introduced by De Bray et al [69], defined it as a cavity ≥ 2 mm in depth and length with a clearly delineated posterior wall on grey-scale ultrasound and a reversed internal flow on Colour-Doppler. In 2012 Muraki et al [70] published new, more straightforward criteria that defined an ulcer as a gap located on the plaque surface that has a lower echogenicity compared to the adjacent intima border of the plaque on B-mode ultrasound. On CEUS a criterion that is used widely for the definition of an ulcer requires the discontinuation of the plaque lumen border for no less than 1x1mm [40] (Figure 4B), (Figure 5).

Figure 5. An asymptomatic 63-year-old female with a plaque ulceration in the origin of the ICA. (A) Colour Doppler Ultrasound reveals an echogenic plaque in the origin of the ICA. However, the exact borders of the plaque cannot be detected due to overwriting artifact. (B) CEUS clearly depicts an ulceration within the plaque (arrowhead) while also allowing for a better visualization of the stenosis. Note that calcifications (arrow) should not be confused with intraplaque enhancement of ulcers.



Πηγή: Rafailidis V, Li X, Sidhu PS, Partovi S, Staub D. Contrast imaging ultrasound for the detection and characterization of carotid vulnerable plaque. *Cardiovasc DiagnTher.* 2020 Aug;10(4):965-981

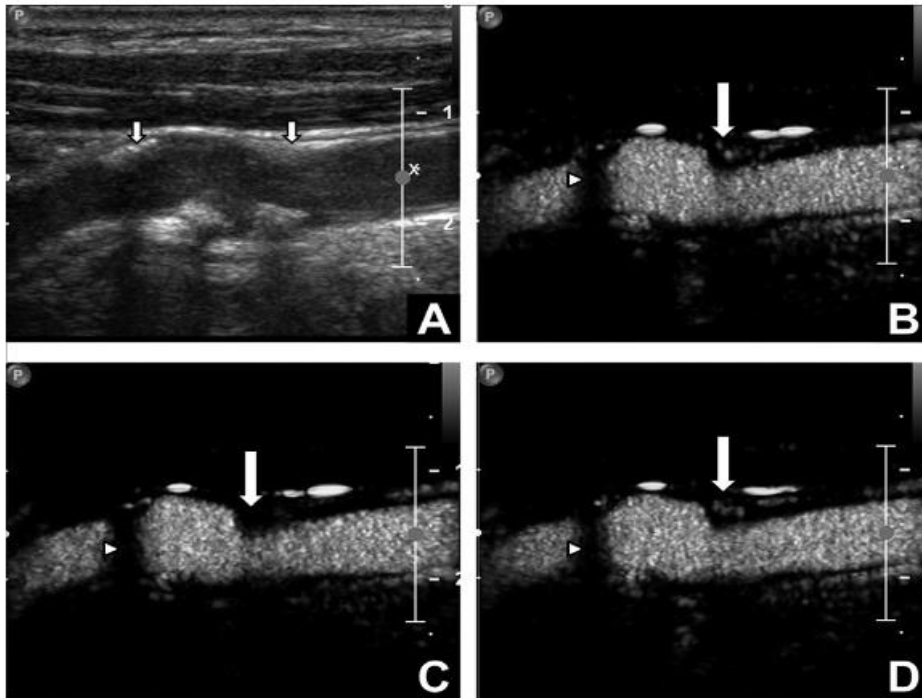
3.3.2 Carotid plaque enhancement and intraplaque neovascularization

Several histopathological reports have shown that the presence of intraplaque neovessels and inflammation both contribute to plaque instability [71, 72]. In comparison to normal micro-vessels, newly formed vasa vasorum often lack the essential pericytes that provide stability making them fragile and more prone to intraplaque hemorrhage [40]. Intraplaque hemorrhage may further destabilize an already vulnerable plaque increasing the risk of rupture. Moreover, inflammatory cells and lipids can penetrate their wall due to the wider

gap junctions of the neo-vessels, leading to plaque enlargement [40]. Furthermore, macrophages release metalloproteinases such as MMP-9, that damage the connecting fibrous tissue, thus further encouraging the growth of these aberrant vasa-vasorum [73]. Therefore, intraplaque neovascularization constitutes a major feature of instability and has become an important target for the evaluation of plaque vulnerability.

CT and MRI have been used for the detection of the intraplaque vascularization but with poor outcomes [40, 74]. The role of CEUS in the evaluation of intraplaque microvasculature evaluation was first described by Feinstein in 2006, by presenting a case report demonstrating the detection of the neovessels with the use of CEUS [40]. Since then, multiple subsequent studies have investigated the possible correlation of ultrasound contrast enhancement with the presence and degree of intraplaque neovascularization. The intraplaque enhancement has been associated with histologically proven newly formed vasa vasorum after endarterectomy, with a correlation between the histological density of these aberrant neovessels and the degree of the enhancement [44]. In another study by Owen et al the usefulness of late enhancement (6 minutes after the intravenous administration) was investigated [49]. Owen et al concluded that the retention of contrast (late enhancement) in an atherosclerotic plaque may represent intraplaque inflammation (Figure 6). Furthermore, various studies have shown that ultrasound contrast enhancement and therefore intraplaque neovascularization is elevated inside echolucent or heterogeneous plaques when compared to echogenic or calcified, in accordance with the increased instability of hypoechoic plaques (44,39). Overall, CEUS is a readily available imaging tool that can provide crucial information about the vulnerability of atherosclerotic plaques by identifying ulcerations as well as intraplaque neovascularization.

Figure 6. Intraplaque neovascularization demonstrated with CEUS. A. B-mode ultrasound revealing atherosclerotic plaques in the bulb and the origin of the ICA - the distal plaque contains calcifications. B-D the arrowheads are demonstrating the shadowing due to the calcifications. B. Contrast enhancement within the plaque can be identified at 0,5sec prior to a high mechanical index flash in order to break down the contrast given. C. Image taken 1,5sec after the flash, showing the disappearance of the enhancement within the plaque. D. Image taken 6 seconds following the flash revealing retention of contrast within the plaque representing intraplaque neovascularization.



Πήγη: Ten Kate GL, van den Oord SC, Sijbrands EJ, van der Lugt A, de Jong N, Bosch JG, van der Steen AF, Schinkel AF. Current status and future developments of contrast-enhanced ultrasound of carotid atherosclerosis. *J Vasc Surg.* 2013 Feb;57(2):539-46.

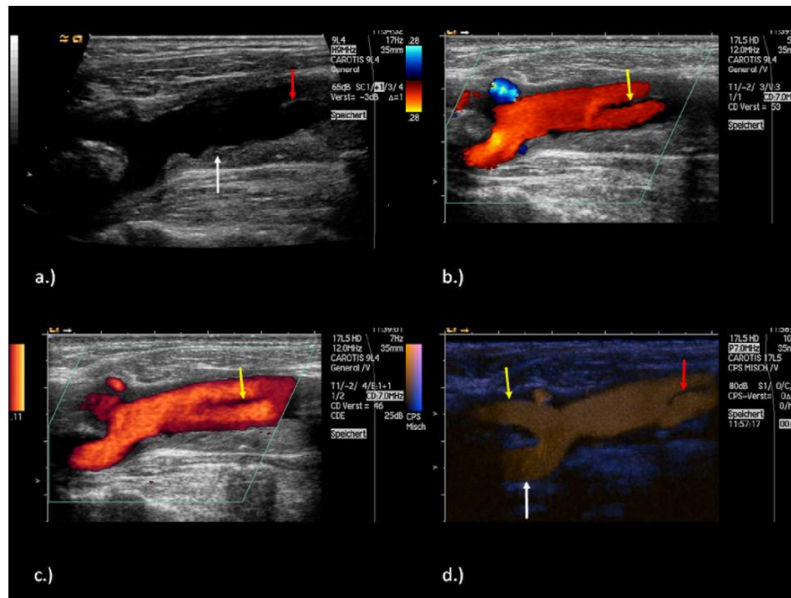
3.4 Other uses of CEUS in the carotid system

3.4.1 Carotid dissection

Carotid artery dissection is an uncommon clinical entity with less than 3 cases per 100.000 patients every year [75]. However, it represents an important risk factor (15-20%) for stroke among young patients [75]. Carotid dissection can be either traumatic, iatrogenic or spontaneous and its clinical symptoms are often inconclusive mainly involving neurological symptoms depending on the affected brain territory. CDU may demonstrate the intramural hematoma and mobile intimal flaps that divide the vessel into a true and a false lumen. The blood flowing within the false lumen is slow thus leading to thrombus formation, occlusion or distal emboli [76]. B-mode ultrasound is the first-line imaging technique in the diagnostic work up of carotid dissection but it has a low sensitivity. MRI is considered the gold standard method for the diagnosis of carotid dissection. However, many patients may have contraindications for the above technique (i.e., pacemaker, old arthroplasty material or chronic renal disease). CEUS constitutes an alternative, readily available, imaging tool improving the diagnostic accuracy of CDU (Figure 7).

Figure 7. CCA dissection. A) CCA (white arrow) dissection and dissection membrane (red arrow) as demonstrated on gray-scale ultrasound. Colour (B) and power (C) doppler

showing the true and the false lumen as well as the dissection membrane. (D) CEUS enabling better visualization of the vessel wall of the ICA (white arrow) and ECA (yellow arrow) as well as the free floating, on-enhancing membrane that represents the intimal flap (red arrow).



Πηγή: Clevert DA, Sommer WH, Zengel P, Helck A, Reiser M. Imaging of carotid arterial diseases with contrast-enhanced ultrasound (CEUS). Eur J Radiol. 2011 Oct;80(1):68-76.

3.4.2 Follow up after stenting/endarterectomy

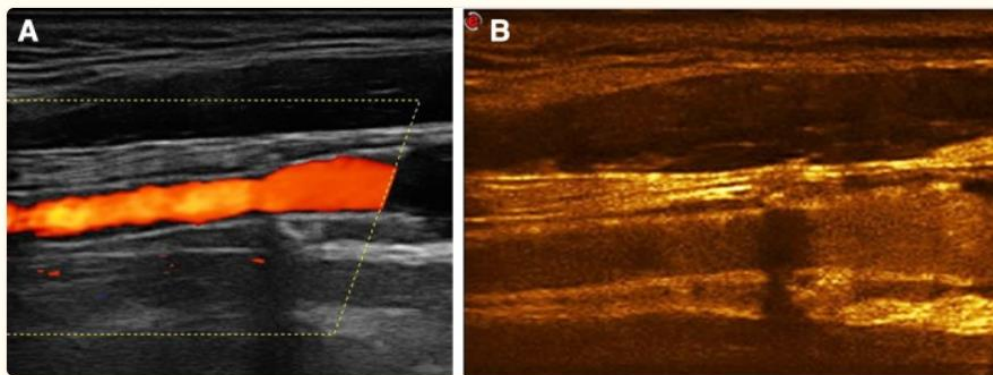
Patients undergoing endarterectomy (EA) or carotid artery stenting (CAS) for the treatment of carotid artery stenosis run the risk of restenosis. In particular, restenosis is estimated to occur in about 25% patients after endarterectomy and in 5% of patients after carotid artery stenting [76]. Several studies have demonstrated that CDU is a sufficient imaging technique for the surveillance of restenosis in patients with CAS. However, the various carotid stenosis criteria should not be used in patients with CAS, due to the fact that the arterial segment with the stent presents a significant elevation of the blood flow due to the different compliance between the stented and unstented part of the vessel wall [77]. The revised criteria for post CAS stenosis are demonstrated in Table 4. CEUS increases the sensitivity of CDU in the diagnosis of restenosis after EA or CAS, by offering a reduction of conventional US flow artefacts as well as better delineation of the whole length and morphology of the stenotic segment of the vessel [55] (Figure 8).

Modified velocity criteria for carotid stent stenosis.

Journal	Stenosis > 20%	Stenosis > 50%	Stenosis > 80%
<i>J Vasc Surg</i> 2008 Jan; 47 (1): 63–73	(PSV $\geq$ 150 cm/s and ICA/CCA ratio $\geq$ 2.15	PSV $\geq$ 220 cm/s and ICA/CCA ratio $\geq$ 2.7	PSV 340 cm/s and ICA/CCA ratio $\geq$ 4.15

Table 4. Modified criteria for post CAS stenosis. Πηγή: Swinnen J. Carotid duplex ultrasound after carotid stenting. *Australas J Ultrasound Med.* 2010 Aug;13(3):20-22.

Figure 8. A sixty-five year old male patient after CAS. (A)CDU demonstrates the patency of the stent although the inside of the stent is not entirely filled, probably due to restenosis or flow artefacts. (B) CEUS sharply demonstrating complete filling of the stent ruling out the possibility of restenosis.



Πηγή: Rafailidis V, Charitanti A, Tegos T, Destanis E, Chrysosgonidis I. Contrast-enhanced ultrasound of the carotid system: a review of the current literature. *J Ultrasound.* 2017 Feb 9;20(2):97-109

3.4.3 Inflammatory conditions of the carotid artery system

Another application of CEUS in the carotid system includes the identification of inflammation of the carotid artery wall in patients with Takayasu arteritis (TA). TA is a granulomatous large vessel vasculitis, with a strong female predilection, that typically damages the aorta and its branches, as well as the renal arteries and the pulmonary artery. [78]. Typical pathological characteristics of TA include inflammation in the adventitia that moves to the intima and in the late stages completely surrounds the vessel resulting in concentric wall thickening leading to stenosis, thrombosis or aneurysm formation [79]. Clinical presentation may vary greatly depending on the degree of inflammation and the

affected vessels. Due to the fact that biopsies in the large arteries are not easily performed, imaging techniques are crucial in order to provide the diagnosis in patients with a suspicion of TA. DSA used to be the gold standard imaging method but has been recently replaced by CTA and MRA, which both have a high sensitivity and specificity for the diagnosis of the disease, allowing the visualization of intramural inflammation [80]. Colour-Doppler ultrasound can also offer crucial information about the morphology of the arteries while it can also detect thrombosis or aneurysms, mainly in the carotid system [80]. The “macaroni sign” indicating the circumferential arterial wall thickening is highly specific for TA. Furthermore, some recent studies have demonstrated that CEUS can improve the quality of the visualization and the definition of the borders of the wall thickening. Contrast-images can clearly demonstrate the presence of contrast enhancement, indicating vascularization, within the affected arterial wall a potential marker for disease activity [51, 52].

Discussion – Future Developments

CDU is the primary radiological technique for patients with suspected carotid arterial diseases. It provides a sufficient visualization of the carotid arteries but it is restricted due to low temporal or spatial resolution, angle dependency and vulnerability to artifacts. CEUS constitutes a safe, non-invasive, fast and valuable tool in the field of vascular pathology. The diagnostic and therapeutic applications of CEUS imaging have been growing rapidly, especially in the field of extracranial carotid arterial pathology. The use of USCA tends to increase the sensitivity of CDU, by overcoming its disadvantages and improving the visualization of the lumen borders, the plaque morphology and the blood flow within the vessel.

One of the most fascinating fields of application of CEUS is the study of the carotid atherosclerotic plaques and specifically the intraplaque neovascularization which has been associated with neurological symptoms. CEUS provided a novel method for the evaluation of intraplaque neovascularization which can be helpful in assessing risk stratification for future cerebrovascular events. Moreover, ultrasound contrast enhancement may indicate not only an elevated vascular density within the plaque but also a loss of vascular integrity which can be caused due to intraplaque hemorrhage, another significant factor of plaque instability. Furthermore, an important number of studies have showed that CEUS is superior to CDU in accurately grading stenosis, detecting vessel wall irregularities and differentiating occlusion from highly stenotic plaques. CEUS can also enable the detection of carotid artery dissection while also it can be used in order to identify carotid wall inflammation in patients with vasculitis. Following up patients after carotid intervention is a promising field of CEUS in need for

further research. Additionally, CEUS can be used as an effective alternative imaging technique in patients with a contraindication for the use of CT or MRI.

Nonetheless, CEUS also has some limitations. Firstly, it is a strongly operator dependent modality. Moreover, calcified plaques that create an acoustic shadow may not allow the complete visualization of the lumen and the plaques as with the conventional ultrasound techniques. Finally, due to the time limitation, it sometimes requires multiple administrations of contrast in order to establish the diagnosis.

On top of its diagnostic applications, CEUS is currently being investigated for its potential therapeutic uses. Recent advances in CEUS include the addition of ligands with a specific target to the contrast microbubbles so that the contrast concentrates on the area of interest, a technique that can be particularly useful in the delivery of chemotherapeutic drugs [81]. It is also possible to place drugs or DNA plasmids within the microbubbles in order to be administered directly to a specific area of the body. This use may also extend to thrombolytic therapies by using microbubble thrombolysis with ultrasound waves [81]. Future research and application of this technology will undoubtedly uncover many more advantages and uses for the treatment of a variety of clinical conditions.

Conclusion

In conclusion, CDU remains the first-line imaging modality for the evaluation of carotid artery diseases, based on its diagnostic value, low cost and wide availability. CEUS constitutes a recent technological development and a complementary imaging technique improving the diagnostic accuracy of conventional ultrasound. It offers better visualization of blood flow inside the lumen without artefacts. It can sharply delineate atherosclerotic plaques, even elongated, while also identifying plaque ulceration and echolucent plaques which can be easily missed with CDU. It can also be used as an alternative imaging technique with a high accuracy for differentiating occlusion and near-occlusion of the ICA while it can also be used for the detection of possible restenosis after carotid angioplasty. Finally, it can be used to visualize and grade intraplaque neovascularization, inflammation of the carotid artery wall and carotid artery dissection. The application of CEUS in the everyday clinical practice is constantly developing and it is expected that its use will be expanded even further in the near future.

References

1. P.N. Burns. Introduction to the physical principles of ultrasound imaging and Doppler (2005): 1-6
2. Hangiandreou, N. J. (2003).AAPM/RSNA Physics Tutorial for Residents: Topics in US. RadioGraphics, 23(4), 1019–1033.doi:10.1148/rg.234035034
3. Bakhru RN, Schweickert WD. Intensive care ultrasound: I. Physics, equipment, and image quality. Ann Am Thorac Soc. 2013 Oct;10(5):540-8. doi: 10.1513/AnnalsATS.201306-191OT. PMID: 24161064; PMCID: PMC5475422.
4. Paefgen V, Doleschel D, Kiessling F. Evolution of contrast agents for ultrasound imaging and ultrasound-mediated drug delivery. Front Pharmacol. 2015 Sep 15;6:197. doi: 10.3389/fphar.2015.00197. PMID: 26441654; PMCID: PMC4584939.
5. Frinking P, Segers T, Luan Y, Tranquart F. Three Decades of Ultrasound Contrast Agents: A Review of the Past, Present and Future Improvements. Ultrasound Med Biol. 2020 Apr;46(4):892-908. doi: 10.1016/j.ultrasmedbio.2019.12.008. Epub 2020 Jan 13. PMID: 31941587.
5. Calliada F, Campani R, Bottinelli O, Bozzini A, Sommaruga MG. Ultrasound contrast agents: basic principles. Eur J Radiol. 1998 May;27 Suppl 2:S157-60. doi: 10.1016/s0720-048x(98)00057-6. PMID: 9652516.
6. Schneider, Michel PhD; Arditi, Marcel PhD; Barrau, Marie-Bernadette PhD; Brochot, Jean BS; Broillet, Anne BS; Ventrone, Roger BS; Yan, Feng PhD. BR1: A New Ultrasonographic Contrast Agent Based on Sulfur Hexafluoride-Filled Microbubbles. Investigative Radiology: August 1995 - Volume 30 - Issue 8 - p 451-457
7. Unger, Evan MD; Shen, Dekang PHD; Fritz, Thomas MSc; Kulik, Brenda BSc; Lund, Pamela MD; Wu, Guan-Li PHD; Yellowhair, David BSc; Ramaswami, Rajan PHD; Matsunaga, TerryPharmD, PHD. Gas-Filled Lipid Bilayers as Ultrasound Contrast Agents. Investigative Radiology: June 1994 - Volume 29 - Issue - p S134-S136
8. Schneider M, Anantharam B, Arditi M, Bokor D, Broillet A, Bussat P, Fouillet X, Frinking P, Tardy I, Terrettaz J, Senior R, Tranquart F. BR38, a new ultrasound blood

pool agent. *Invest Radiol*. 2011 Aug;46(8):486-94. doi: 10.1097/RLI.0b013e318217b821. PMID: 21487303.

9. Feinstein S. B., Cheirif J., Ten Cate F. J., Silverman P. R., Heidenreich P. A., Dick C., et al. (1990). Safety and efficacy of a new transpulmonary ultrasound contrast agent: initial multicenter clinical results. *J. Am. Coll. Cardiol*. 16 316–324. 10.1016/0735-1097(90)90580-I

10. Esposito F, Di Serafino M, Sgambati P et al. Ultrasound Contrast Media in Paediatric Patients: Is It an Off-Label Use? Regulatory Requirements and Radiologist's Liability. *Radiol med*. 2011;117(1):148-59. doi:10.1007/s11547-011-0718-1

11. Blomley M.J.K., Cooke, J.C., et al. "Microbubble contrast agents: a new era in ultrasound", *BMJ*., 2001, 322(7296), 1222–1225.

12. Quaia E (2005) Classification and safety of microbubble-based contrast agents. In: Quaia E (ed) *Contrast media in ultrasonography: basic principles and clinical applications*. Springer, Berlin Heidelberg New York, pp 2–14

13. Correias JM, Bridal L, Lesavre A et al (2001) Ultrasound contrast agents: properties, principles of action, tolerance and artifacts. *EurRadiol* 11:1316–1328

14. Chung YE, Kim KW. Contrast-enhanced ultrasonography: advance and current status in abdominal imaging. *Ultrasonography*. 2015 Jan;34(1):3-18.

15. Lindner JR. Microbubbles in medical imaging: current applications and future directions. *Nat Rev Drug Discov*. 2004 Jun;3(6):527-32. doi: 10.1038/nrd1417. PMID: 15173842.

16. Dindyal S, Kyriakides C. Ultrasound microbubble contrast and current clinical applications. *Recent Pat Cardiovasc Drug Discov*. 2011 Jan;6(1):27-41. doi: 10.2174/157489011794578446. PMID: 21222650.

17. Hu C, Feng Y, Huang P, Jin J. Adverse reactions after the use of SonoVue contrast agent: Characteristics and nursing care experience. *Medicine (Baltimore)*. 2019 Nov;98(44):e17745.

18. Rott HD (1999) Safety of ultrasonic contrast agents. European Committee for Medical Ultrasound Safety. *Eur J Ultrasound* 9:195-197

19. Lasser EC, Lyon SG, Berry CC. Reports on contrast media reactions: analysis of data from reports to the U.S. Food and Drug Administration. *Radiology* 1997;203:605–10.

20. Piscaglia F, Bolondi L. The safety of SonoVue in abdominal applications: retrospective analysis of 23,188 investigations. *Ultrasound Med Biol* 2006;32:1369–75

21. P.A. Dijkmans, C.A. Visser, O. Kamp, Adverse reactions to ultrasound contrast agents: Is the risk worth the benefit?, *European Journal of Echocardiography*, Volume 6, Issue 5, 01 October 2005, Pages 363–366
22. Main ML Goldman JH Grayburn PA Thinking outside the "box"-the ultrasound contrast controversy *Journal of the American College of Cardiology* 50 2007. 2434–2437. 10.1016/j.jacc.2007.11.006
23. Taiyeb M Khumri, Michael L Main, Safety and Risk-Benefit Profile of Microbubble Contrast Agents in Echocardiography, *US Cardiology* 2009;6(1):16–9
24. Appis AW, Tracy MJ, Feinstein SB. Update on the safety and efficacy of commercial ultrasound contrast agents in cardiac applications. *Echo Res Pract.* 2015 Jun 1;2(2):R55-62
25. Chang EH. An Introduction to Contrast-Enhanced Ultrasound for Nephrologists. *Nephron.* 2018;138(3):176-185.
26. de Jong N. Physics of microbubble scattering. In: Nanda N, Schlieff R, Goldberg B, editors. *Advances in Echo Imaging Using Contrast Enhancement*. Dordrecht: Kluwer, 1997:39–64.
27. Brinjikji W, Huston J 3rd, Rabinstein AA, Kim GM, Lerman A, Lanzino G. Contemporary carotid imaging: from degree of stenosis to plaque vulnerability. *J Neurosurg.* 2016 Jan;124(1):27-42.
28. Del Brutto VJ, Gornik HL, Rundek T. Why are we still debating criteria for carotid artery stenosis? *Ann Transl Med.* 2020 Oct;8(19):1270.
29. Lee W. General principles of carotid Doppler ultrasonography. *Ultrasonography.* 2014 Jan;33(1):11-7.
30. Casadei A, Floreani M, Catalini R, Serra C, Assanti AP, Conci P. Sonographic characteristics of carotid artery plaques: Implications for follow-up planning? *J Ultrasound.* 2012 Sep;15(3):151-7.
31. O'Donnell TF, Jr, Erdoes L, Mackey WC, McCullough J, Shepard A, Heggerick P, et al. Correlation of B-mode ultrasound imaging and arteriography with pathologic findings at carotid endarterectomy. *Arch Surg.* 1985;120:443–449.
32. Baud JM, Stanciu D, Yeung J, Maurizot A, Chabay S, de Malherbe M, Chadenat ML, Bachelet D, Pico F. Contrast enhanced ultrasound of carotid plaque in acute ischemic stroke (CUSCAS study). *Rev Neurol (Paris).* 2021 Jan-Feb;177(1-2):115-123.

33. Clevert DA, Sommer WH, Helck A, Saam T, Reiser M. Improved carotid atherosclerotic plaques imaging with contrast-enhanced ultrasound (CEUS). *Clin Hemorheol Microcirc.* 2011;48(1):141-8.
34. Kono Y, Pinnell SP, Sirlin CB, Sparks SR, Georgy B, Wong W, Mattrey RF (2004) Carotid arteries: contrast-enhanced US angiography—preliminary clinical experience. *Radiology* 230:561–568.
35. Holden A, Hope JK, Osborne M, Moriarty M, Lee K. Value of a contrast agent in equivocal carotid ultrasound studies: pictorial essay. *Australas Radiol.* 2000 Aug;44(3):253-60.
36. Hammond CJ, McPherson SJ, Patel JV, Gough MJ. Assessment of apparent internal carotid occlusion on ultrasound: prospective comparison of contrast-enhanced ultrasound, magnetic resonance angiography and digital subtraction angiography. *Eur J Vasc Endovasc Surg.* 2008 Apr;35(4):405-12
37. Ventura CA, Silva ES, Cerri GG, Leão PP, Tachibana A, Chammas MC. Can contrast-enhanced ultrasound with second-generation contrast agents replace computed tomography angiography for distinguishing between occlusion and pseudo-occlusion of the internal carotid artery? *Clinics (Sao Paulo).* 2015 Jan;70(1):1-6.
38. van den Oord SC, ten Kate GL, Akkus Z, Renaud G, Sijbrands EJ, ten Cate FJ, van der Lugt A, Bosch JG, de Jong N, van der Steen AF, Schinkel AF. Assessment of subclinical atherosclerosis using contrast-enhanced ultrasound. *Eur Heart J Cardiovasc Imaging.* 2013 Jan;14(1):56-61.
39. Xiong L, Deng YB, Zhu Y, Liu YN, Bi XJ. Correlation of carotid plaque neovascularization detected by using contrast-enhanced US with clinical symptoms. *Radiology.* 2009;251:583–589.
40. ten Kate GL, van Dijk AC, van den Oord SC, Hussain B, Verhagen HJ, Sijbrands EJ, van der Steen AF, van der Lugt A, Schinkel AF. Usefulness of contrast-enhanced ultrasound for detection of carotid plaque ulceration in patients with symptomatic carotid atherosclerosis. *Am J Cardiol.* 2013 Jul 15;112(2):292-8.
41. Varetto G, Gibello L, Bergamasco L, Sapino A, Castellano I, Garneri P, Rispoli P. Contrast enhanced ultrasound in atherosclerotic carotid artery disease. *Int Angiol.* 2012 Dec;31(6):565-71. PMID: 23222935.

42. Macioch JE, Katsamakis CD, Robin J, Liebson PR, Meyer PM, Geohas C, Raichlen JS, Davidson MH, Feinstein SB. Effect of contrast enhancement on measurement of carotid artery intimal medial thickness. *Vasc Med*. 2004 Feb;9(1):7-12.
43. Müller HF, Viaccoz A, Kuzmanovic I, Bonvin C, Burkhardt K, Bochaton-Piallat ML, Sztajzel R. Contrast-enhanced ultrasound imaging of carotid plaque neo-vascularization: accuracy of visual analysis. *Ultrasound Med Biol*. 2014 Jan;40(1):18-24.
44. Coli S, Magnoni M, Sangiorgi G, et al. Contrast-enhanced ultrasound imaging of intraplaque neovascularization in carotid arteries: correlation with histology and plaque echogenicity. *J Am Coll Cardiol*. 2008;52:223–230.
45. Zhou Y, Xing Y, Li Y, Bai Y, Chen Y, Sun X, Zhu Y, Wu J. An assessment of the vulnerability of carotid plaques: a comparative study between intraplaque neovascularization and plaque echogenicity. *BMC Med Imaging*. 2013 Mar 28;13:13
46. Faggioli GL, Pini R, Mauro R, Pasquinelli G, Fittipaldi S, Freyrie A, Serra C, Stella A. Identification of carotid 'vulnerable plaque' by contrast-enhanced ultrasonography: correlation with plaque histology, symptoms and cerebral computed tomography. *Eur J Vasc Endovasc Surg*. 2011 Feb;41(2):238-48. Doi
47. Hoogi A, Adam D, Hoffman A, Kerner H, Reisner S, Gaitini D. Carotid plaque vulnerability: quantification of neovascularization on contrast-enhanced ultrasound with histopathologic correlation. *AJR Am J Roentgenol*. 2011 Feb;196(2):431-6
48. Giannoni MF, Vicenzini E, Citone M, Ricciardi MC, Irace L, Laurito A, Scucchi LF, Di Piero V, Gossetti B, Mauriello A, Spagnoli LG, Lenzi GL, Valentini FB. Contrast carotid ultrasound for the detection of unstable plaques with neoangiogenesis: a pilot study. *Eur J Vasc Endovasc Surg*. 2009 Jun;37(6):722-7
49. Owen DR, Shalhoub J, Miller S, Gauthier T, Doryforou O, Davies AH, et al. Inflammation within carotid atherosclerotic plaque: assessment with late-phase contrast-enhanced US. *Radiology* 2010;255:638-44
50. Ma LY, Li CL, Ma LL, Cui XM, Dai XM, Sun Y, Chen HY, Huang BJ, Jiang LD. Value of contrast-enhanced ultrasonography of the carotid artery for evaluating disease activity in Takayasu arteritis. *Arthritis Res Ther*. 2019 Jan 16;21(1):24.
51. Magnoni M, Dagna L, Coli S, Cianflone D, Sabbadini MG, Maseri A. Assessment of Takayasu arteritis activity by carotid contrast-enhanced ultrasound. *Circ Cardiovasc Imaging*. 2011 Mar;4(2):e1-2.

52. Schinkel AF, van den Oord SC, van der Steen AF, van Laar JA, Sijbrands EJ. Utility of contrast-enhanced ultrasound for the assessment of the carotid artery wall in patients with Takayasu or giant cell arteritis. *Eur Heart J Cardiovasc Imaging*. 2014;15(5):541–6.
53. Clevert DA, Sommer WH, Helck A, Reiser M. Duplex and contrast enhanced ultrasound (CEUS) in evaluation of in-stent restenosis after carotid stenting. *Clin Hemorheol Microcirc*. 2011;48(1):199-208.
54. Li ZJ, Luo XH, Du LF. Identification of carotid artery dissection by contrast enhanced ultrasonograph. A case report. *Med Ultrason*. 2015 Dec;17(4):564-5.
55. Rafailidis V, Charitanti A, Tegos T, Destanis E, Chrysosgonidis I. Contrast-enhanced ultrasound of the carotid system: a review of the current literature. *J Ultrasound*. 2017 Feb 9;20(2):97-109
56. Sirlin CB, Lee YZ, Girard MS, Peterson TM, Steinbach GC, Baker KG, Mattrey RF (2001) Contrast-enhanced B-mode US angiography in the assessment of experimental in vivo and in vitro atherosclerotic disease. *AcadRadiol* 8:162–172
57. Piscaglia F, Nolsøe C, Dietrich CF, et al: The EFSUMB guidelines and recommendations on the clinical practice of contrast enhanced ultrasound (CEUS): Update 2011 on non-hepatic applications. *Ultraschall Med* 33 (1):33-59, 2012
58. Clevert DA, Helck A, Paprottka PM, et al: Contrast-enhanced ultrasound imaging of the carotid artery. *Radiologe* 51 (6):483-489, 2011
59. Norris JW, Zhu CZ, Bornstein NM, Chambers BR. Vascular risks of asymptomatic carotid stenosis. *Stroke*. 1991 Dec;22(12):1485-90.
60. Johansson E, Fox AJ. Carotid Near-Occlusion: A Comprehensive Review, Part 1-- Definition, Terminology, and Diagnosis. *AJNR Am J Neuroradiol* 2016;37:2-10. 10.3174/ajnr.A4432
62. Rafailidis V, Li X, Sidhu PS, Partovi S, Staub D. Contrast imaging ultrasound for the detection and characterization of carotid vulnerable plaque. *Cardiovasc DiagnTher*. 2020 Aug;10(4):965-981.
63. Topakian R, King A, Kwon SU, Schaafsma A, Shipley M, Markus HS, et al. Ultrasonic plaque echolucency and emboli signals predict stroke in asymptomatic carotid stenosis. *Neurology*. 2011;77:751–8.

64. Kuk M, Wannarong T, Beletsky V, Parraga G, Fenster A, Spence JD. Volume of carotid artery ulceration as a predictor of cardiovascular events. *Stroke*. 2014;45:1437–41. doi: 10.1161/STROKEAHA.114.005163.
65. Staub D, Partovi S, Imfeld S, Uthoff H, Baldi T, Aschwanden M, Jaeger K. Novel applications of contrast-enhanced ultrasound imaging in vascular medicine. *Vasa*. 2013 Jan;42(1):17-31.
66. Skagen K, Skjelland M, Zamani M, Russell D. Unstable carotid artery plaque: new insights and controversies in diagnostics and treatment. *Croat Med J*. 2016 Aug 31;57(4):311-20.
67. Brinjikji W, Rabinstein AA, Lanzino G, et al. Ultrasound characteristics of symptomatic carotid plaques: a systematic review and meta-analysis. *Cerebrovasc Dis*. 2015;40(3-4):165–174. doi: 10.1159/000437339.
68. Rafailidis V, Chrysosgonidis I, Tegos T, Kouskouras K, Charitanti-Kouridou A. Imaging of the ulcerated carotid atherosclerotic plaque: a review of the literature. *Insights Imaging*. 2017 Apr;8(2):213-225.
69. de Bray JM, Baud JM, Dauzat M. Consensus concerning the morphology and the risk of carotid plaques. *Cerebrovasc Dis*. 1997;7:289–296.
70. Muraki M, Mikami T, Yoshimoto T, et al. New criteria for the sonographic diagnosis of a plaque ulcer in the extracranial carotid artery. *AJR Am J Roentgenol*. 2012;198(5):1161–1166.
71. McCarthy M, Loftus I, Thompson M, et al. Angiogenesis and the atherosclerotic carotid plaque: an association between symptomatology and plaque morphology. *J Vasc Surg* 1999;30:261-8. 10.1016/S0741-5214(99)70136-9
72. Alexandratou M, Papachristodoulou A, Li X, Partovi S, Davidhi A, Rafailidis V, Prassopoulos P, Kamperidis V, Koutroulou I, Tsvigoulis G, Grigoriadis N, Krogias C, Karapanayiotides T. Advances in Noninvasive Carotid Wall Imaging with Ultrasound: A Narrative Review. *Journal of Clinical Medicine*. 2022; 11(20):6196.
73. Varetto G, Gibello L, Castagno C, Quaglino S, Ripepi M, Benintende E, Gattuso A, Garneri P, Zan S, Capaldi G, Bertoldo U, Rispoli P. Use of Contrast-Enhanced Ultrasound in Carotid Atherosclerotic Disease: Limits and Perspectives. *Biomed Res Int*. 2015;2015:293163.

74. Granada JF, Feinstein SB (2008) Imaging of the vasa vasorum. *Nat Clin Pract Cardiovasc Med.* 5:S18–S25
75. Guillon B, Bousser MG. Epidemiology and pathophysiology of spontaneous cervical artery dissection. *J Neuroradiol.* 2002;29:241–249.
76. Clevert DA, Sommer WH, Zengel P, Helck A, Reiser M. Imaging of carotid arterial diseases with contrast-enhanced ultrasound (CEUS) *Eur J Radiol.* 2011;80:68–76.
77. Swinnen J. Carotid duplex ultrasound after carotid stenting. *Australas J Ultrasound Med.* 2010 Aug;13(3):20-22.
78. Ma, LY., Li, CL., Ma, LL. *et al.* Value of contrast-enhanced ultrasonography of the carotid artery for evaluating disease activity in Takayasu arteritis. *Arthritis Res Ther* **21**, 24 (2019).
79. Zhu FP, Luo S, Wang ZJ, Jin ZY, Zhang LJ, Lu GM. Takayasu arteritis: imaging spectrum at multidetector CT angiography. *Br J Radiol.* 2012 Dec;85(1020):e1282-92.
80. Russo RAG, Katsicas MM. Takayasu Arteritis. *Front Pediatr.* 2018 Sep 24;6:265.
81. Mehta KS, Lee JJ, Taha AG, Avgerinos E, Chaer RA. Vascular applications of contrast-enhanced ultrasound imaging. *J Vasc Surg.* 2017 Jul;66(1):266-274.