Ultrasound Elastography: another piece in the puzzle of carotid plaque vulnerability?

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Abstract
Recent literature has shown that various carotid plaque features, other than stenosis, contribute to plaque vulnerability. Features such as surface morphology and plaque composition with distinct components (e.g. intraplaque hemorrhage, lipid core) have been associated with the increased risk of future cerebrovascular events. Ultrasonography constitutes the first line modality for the assessment of carotid disease and has traditionally been used to grade stenosis with high accuracy. Recent technological advances such as contrast-enhanced ultrasound and elastography increased the diagnostic yield of ultrasound in assessing the morphology of carotid plaques. The purpose of this review is to present the available literature on ultrasound elastography of the atherosclerotic carotid. Strain and shear wave elastography allow for the characterization of plaque components, thus indicating its nature and importantly, the plaque’s vulnerability. Shear wave elastography indices appear more robust than Strain indices. Overall, elastography is a feasible method to distinguish vulnerable carotid plaques. There is, however, a need for larger and longer prospective controlled clinical studies in order to validate elastography as an imaging modality used for the detection of unstable carotid plaques.

Keywords: ultrasound imaging; carotid artery; elastography

Introduction
Carotid atherosclerotic plaque and its rupture are one of the most frequent causes of cerebrovascular events. Up to 80% of strokes are ischemic in etiology [1], with 10% -20% attributable to cerebral micro-embolism [2]. Carotid plaques have different histologic components, including lipid, fibrous, or calcified tissue. The quantification of these components and the resulting characterization of a plaque - as vulnerable or stable - represent a major field in current imaging research. They may predict the future stroke risks and open the opportunity for prevention by early plaque- and risk-specific treatments.
Young’s modulus (YM), bulk modulus, or shear modulus quantifies the amount of stress needed to achieve a unit of strain and measures the tissue’s elasticity or elastic modulus. Two methods exist for the measurement of the elastic deformation of a tissue; strain (SE) and shear wave elastography (SWE) \([6,7]\). SE measures the plaque’s displacement caused by an external force, such as blood pressure oscillations.

Through deformation estimating algorithms (e.g., cross-correlation measurements or optical flow methods), strain elastography calculates semi-quantitative parameters such as strain, strain velocities or strain rate.

In SWE, the transducer emits shear waves through an acoustic radiation force impulse (ARFI) \([8]\). These waves disseminate perpendicularly to the impulse. The technique measures the velocity by which shear waves propagate through the tissue, expressed as YM \([6]\). YM defines the tissue’s resistance to elastic deformation and depends on its composition. Soft tissues, such as a plaque’s lipid core, demonstrate significant elastic deformation, a lower YM and lower shear wave velocities; more rigid tissues and lesions demonstrate less elastic deformation \([9]\).

Unstable plaques show various displacement patterns \([10-12]\) depending on the plaque composition. In general, fatty elements are softer than fibrous tissue \([9-13]\); hence soft plaques (e.g., plaques with an extensive fatty nucleus, intraplaque hemorrhage) show more extensive deformation. The distribution of deformation in a plaque is directly related to its composition. Even small foci of soft areas demonstrate higher deformation values \([14-16]\). Vulnerable carotid plaques are softer than stable ones \([16,17]\), a hypothesis currently explored with quantitative evaluation indices. Elastic or structural heterogeneity \([18,19]\) is another index, where the deformation detected by elastography depends on the plaque heterogeneity and differences between the carotid’s blood pressure and the plaque’s structure.

This review aims to summarize the available literature on elastography of atherosclerotic carotid, to present evidence on the efficacy of Strain and SWE elastography to characterize carotid plaques’ vulnerability and the potential of elastography as a prognostic tool to stratify stroke risk.

**Material and methods**

The literature search was performed with MEDLINE via the PUBMED search engine on January 20, 2021. The following keywords were applied: “carotid” AND “plaque” AND “ultrasound” AND “elastography.” The original list consisted of 103 articles. Figure 1 depicts the PRISMA flow chart. We excluded 18 articles because of irrelevant article titles and one because of duplication. The remaining articles’ exclusion criteria were: editorials, case reports or series with less than five patients, letters to editor, literature reviews, animal studies, studies performed in phantom vessels, studies on intravascular US, and studies on mathematical optimization of elastography parameters. Furthermore, after reading the abstracts, articles not related to carotid plaques’ vulnerability studied in elastography in human subjects were excluded, as well the non-English language articles.

The cases presented as images in this review were examined in our department.

Twenty-one articles met the inclusion criteria and reported on elastography ability to characterize a carotid plaque as stable or unstable or distinguish between asymptomatic and symptomatic patients.

**Results**

We extracted the following data: a) study design, b) the total number of patients, c) the total number of plaques, d) elastography technique, e) reference method, f) conclusion (Table I).

All included articles were comparative studies and concluded that elastography is efficient in assessing carotid atherosclerotic plaques. Articles compared indices of SE or SWE/ARFI elastography for the non-invasive identification of vulnerable carotid plaques in patients with or without ischemic stroke symptoms. The reference was either another imaging modality \((n=7)\), the clinical
Table I. Extracted data from the included articles

| Authors, Year | Patients | Plaques studied | Elastography technique | Reference method | Conclusion |
|---------------|----------|-----------------|------------------------|------------------|------------|
| Wang, 2016 [21] | 75 | 75 | SE | Cognitive performance | Statistically significant correlations between maximum strain indices and total cognition (p<0.05) |
| Wang, 2014 [20] | 24 | 24 | SE | Cognitive performance | Negative correlation between axial, lateral strain indices and cognitive function |
| Wang, 2015 [23] | 24 | 24 | SE | Cognitive performance | Improved strain-cognition correlation when adventitia included |
| Cloutier, 2018 [22] | 66 | 132 | SE | Neurological symptoms | Symptomatic stenosis showed lower axial strain_max and axial shear strain_max on symptomatic stenosis compared to asymptomatic. Combination of strain, shear, and echogenicity showed a sensitivity and specificity of 71-79%. |
| Naim, 2013 [25] | 31 | 31 | SE | MRI | Lower strain in plaques containing a lipid core. |
| Huang, 2015 [27] | 197 | 46 | SE | MRI | High local strain rate and spatially non-uniform strain rate distributions on vulnerable plaques. |
| Roy-Cardinal, 2017 [24] | 31 | 31 | SE | MRI | Increased cumulated axial strain/cumulated axial translation (AUC=0.886), the most discriminating parameter for vulnerable plaque. |
| Huang, 2017 [26] | 52 | 80 | SE | MRI | Larger local deformations and increased complexity in deformation patterns more likely in vulnerable plaques. |
| Liu, 2019 [28] | 32 | 53 | SE | MRI | Validation of the inter-operator reproducibility of carotid elastography for identifying vulnerable carotid plaques | (sensitivity=71.4%, specificity=87.1%, accuracy=82.2%). |
| Zhang, 2015 [31] | 29 | 38 | SE | Histology, CEUS | Softer and more elastically heterogeneous plaques as IPN increased. |
| Liu, 2014 [29] | 19 | 19 | SE | Histology, US | Sensitivity, specificity, and accuracy of SE for detecting vulnerable plaques were 50%, 100%, and 89.4%, respectively (k=0.612, p=0.004). |
| Hansen, 2016 [30] | 34 | 34 | SE | Histology | Locally elevated strain values in plaques’ regions that predominantly contained vulnerability-related components. |
| Lou, 2017 [32] | 61 | 271 | SWE | Neurological symptoms | Lower mean YM in plaques of symptomatic group compared to the asymptomatic group. |
| Shang, 2018 [33] | 142 | 129 | SWE | Neurological symptoms; Serum homocysteine level | SWV lower in hypoechoic plaques. Lower mean values of SWV in symptomatic ischemic stroke. Serum homocysteine levels negatively correlated with minimal SWV. |
| Rammarine, 2014 [34] | 81 | 52 | SWE | Neurological symptoms | Lower mean YM in plaques of symptomatic patients than in the asymptomatic. |
| Marlevi, 2020 [35] | 20 | 27 | SWE | MRI | Higher group and phase velocity (SWE biomarkers) in vulnerable plaques, type VI, compared to any other AHA plaque type. |
| Doherty, 2015 [36] | 5 | 5 | ARFI | MRI | Correspondence of increased ARFI displacements in regions identified as lipid on MRI. |
| Torres, 2019 [37] | 25 | 25 | ARFI | Histology | Developing a new outcome metric (log(VoA)) that can differentiate components of the same stiffness (NC from IPH, COL from CAL) |
| Czernuszewicz, 2017 [38] | 25 | 17 | ARFI | Histology | ARFI is feasible to distinguish soft from stiff plaque components and measure FC thickness. |
| Garrard, 2015 [39] | 25 | 25 | SWE | Histology | Lower mean YM in vulnerable plaques than in non-vulnerable. YM not correlated with GSM |
| Di Leo, 2018 [40] | 43 | 43 | SWE (Multiparametric US) | Histology; CTA | High sensitivity (87.1%) of SWE and higher specificity compared to CEUS (66.7% vs.58.3%) in identifying vulnerable plaques. |
status of the patients (n=7) or histopathology alone (n=4) or combined with imaging modalities (n=3).

Eleven articles studied semi-quantitative SE. Three of them [20-22] validated elastography against ischemic symptoms and found that specific parameters (e.g., maximum strain indices) correlate with neurological symptoms and may predict cognitive impairment [21]. Higher values of some indices (e.g., axial and lateral strain) were associated with a more significant cognitive function decline [20]. Furthermore, by including the adventitial layer in the plaque’s demarcation, Wang et al. [23] found an improved correlation between strain and cognition as the method provided more information on the strain distribution inside and around the plaque. However, another study found higher maximum values of indexes (axial strain, axial shear strain) in asymptomatic patients’ plaques, raising questions on SE value for plaque vulnerability characterization [22].

Five studies compared SE with MRI [24-28]. One study validated the inter-operator reproducibility in the detection of unstable, vulnerable plaques with the use of a specific index of strain (axial strain rate - ASR) and showed high sensitivity (71.4%), specificity (87.1%), and accuracy (82.2%) for the method [28]. Other studies examined different strain elastography parameters (local strain rate, cumulated axial strain/cumulated axial translation, axial strain) and found that higher values are associated with unstable plaques [24,26,27]. Unstable plaques also showed higher deformation values and a higher degree of heterogeneity [26]. Moreover, Huang et el. compared strain indices with plaque textural analysis and found that the method is feasible and may distinguish vulnerable from nonvulnerable carotid plaques [26]. Another study reported lower strain elastography values for unstable carotid plaques [24]. However, this is not corroborated by studies that used non-invasive strain measurements and endovascular elastography.

The concept that unstable plaques demonstrate increased strain indices has gathered strong support by studies using histopathology as a reference [7,29-31]. Histopathology classifies plaques according to the AHA classification and composition. Increased strain indices corresponded to plaques or plaques’ areas characterized histologically as unstable, while low values corresponded to plaques rich in fibrous tissue and collagen [30]. With histology as the reference method, elastography was superior to conventional ultrasound for unstable plaque identification, with a sensitivity of 50%, a specificity of 100%, and an accuracy of 89.4% [30]. Finally, unstable plaques with a high degree of elastic heterogeneity showed significant intraplaque neovascularization [31], attesting to the multifaceted nature of plaque vulnerability.

Nine articles [32–40] studied quantitative parameters of SWE, of which three studied ARFI indices [36–38], and one assessed quantitatively and qualitatively carotid atherosclerotic plaques [38]. The most important index of SWE, Young’s modulus (YM), showed lower mean values in plaques of symptomatic compared to asymptomatic patients (fig 2) [32,34]. Other SWE indices, such as the shear wave propagation velocity (SWV), showed lower mean values in symptomatic patients and hypoechoic plaques [33]. The same study compared SWV values to homocysteine serum levels, a stroke biomarker in patients with cerebrovascular accidents, and found negative correlation between them: the higher the homocysteine serum levels, the lower the values of SWV in plaques of patients with strokes.

Fig 2. SWE quantitative assessment of three different types of atherosclerotic carotid plaques: (a) After plaque’s segmentation, YM is measured. The lower values of YM corresponds to the hypo-echoic nature of the plaque (type II, according to Gououlakos-Nikolaides (G-N) categorization), indicating plaque’s vulnerability. Note plaque’s heterogeneity and irregular contour; (b) Type III plaque, according to G-N categorization, at carotid bulb. YM value and color map of the plaque agree with plaque’s echogenicity; (c) Type IV plaque, according to G-N categorization. SWE indices values (YM, SWV) are compatible with plaque’s echogenicity. E1: YM, V1: SWV
Another article compared SWE and ARFI elastography to MRI findings in unstable plaques and introduced two new biomarkers; group velocity and frequency-dependent phase velocities [35]. Following AHA classification, these indices distinguished unstable plaques from other carotid plaques, particularly type IV. Moreover, areas characterized as fatty on MRI were identified on ARFI elastography as areas of increased tissue deformation, enhancing the method’s ability to detect unstable plaques [36].

There are studies that compared SWE with histopathological features of carotid plaques [37–40]. Low YM values and low mean YM values were associated with plaques characterized histologically as unstable [40]. Czernuszewicz et al found that ARFI elastography might measure the fibrous cap and differentiate the plaque composition [38]. A new outcome metric of ARFI, log(VoA), allows the distinction of fibrous tissue from calcifications, and fatty necrotic core from intraplaque hemorrhage, essential elements of unstable plaques [37]. Correlated to histology, SWE shows high sensitivity (87.1%) – same as CT angiography – and higher specificity compared to CEUS (66.7% vs. 58.3%) for the identification of carotid plaques prone to rupture (fig 3) [40].

**Discussion**

Quantifying a plaque’s composition and further characterizing the plaque as unstable or stable - before a stroke occurs - is currently an important research topic that may contribute to the prevention and treatment of atherosclerosis. Plaques with a large fatty necrotic nucleus coated by a thin fibrous cap, intraplaque hemorrhage, neovascularization, or inflammation, are more prone to rupture [41,42]. Ultrasound-based elastography assesses the mechanical properties of the carotid plaque by measuring the plaque displacement and deformation. Several research studies have highlighted elastography as a method able to characterize the carotid plaque and categorize it according to the risk of rupture [14,16,43–46]. The distribution of plaque deformation is directly related to its local composition [14–16]. Elastography was useful for assessing carotid atherosclerotic plaques, especially in combination with other ultrasound techniques in multi-parametric ultrasound settings (fig 4) [40]. Results are unequivocal for SWE but less so for strain elastography. Indices of SWE, mainly YM and SWV, were reliable for evaluating carotid plaque against any reference (clinical status, laboratory markers, imaging, histology). SWV demonstrated a negative correlation with laboratory markers, such as homocysteine serum levels [33]. Diagnostic accuracy increased with the inclusion of the fibrous cap’s thickness in the measurements, with a
smaller thickness associated with a higher rupture risk at a cut-off value of 0.5 mm [38]. However, this particular study’s limitation was the small number of samples with a fibrous cap thickness <0.5 mm. ARFI elastography identified unstable plaques and even differentiated elements of similar texture, such as fatty nucleus from intraplaque hemorrhage [37].

The correlation of strain elastography with ischemic stroke symptoms implies a potential role in evaluating carotid plaques in ischemic stroke patients [21]. The negative correlation of strain indices with the patients’ cognitive function [20] could be potentially significant in managing this subgroup of patients. Comparison of strain indices with other imaging indices of carotid plaque instability (e.g., MRI, CEUS) suggests that elastographic strain indices may be able to differentiate unstable plaques by identifying unstable focal areas or whole unstable plaques [27], increased heterogeneity, or a high proportion of soft texture [31]. Elastography was also able to identify histologically characterized unstable plaques. Not in line with these results, Cloutier et al. found that the maximum values of strain indices are lower in symptomatic than in asymptomatic patients. However, this study examined plaques with small fatty regions in patients who underwent ultrasound examinations three weeks after the onset of symptoms, factors that may have affected the strain parameters. Another equivocal study [25] reported lower strain values in the plaques’ fatty nuclei. However, this study measured strain with a non-commercially available method. These findings are at odds with the studies mentioned above and other studies that used intravascular ultrasound [47].

The heterogeneity of strain indices values [22,25] raises doubts as to the efficacy of strain elastography in assessing carotid atherosclerotic plaques (semi-quantitative assessment) and reflects the lack of unanimity for the assessment of carotid plaques. Unlike strain, SWE appears more reliable for distinguishing vulnerable carotid plaques, as the results are more homogeneous and quantifiable [33,37,38,40].

As an overview, the studies included showed heterogeneity, and in some cases, contradictory findings [22,25]. No validated cut-off values for carotid plaque elastography exist and values among ultrasound manufacturers may be different. The number of patients in studies varied significantly and was too small to evaluate the clinical value of elastography.

Despite the limitations mentioned, elastography has many advantages. It is a non-invasive, easily accessible, safe, and technically easy imaging modality, with high sensitivity and greater specificity than conventional ultrasound. Elastography is a potential diagnostic tool that may improve vulnerable plaque detection and stroke risk stratification.

More extensive prospective controlled studies on the elastography of carotid plaques are required, as are clinical trials assessing the technique’s ability to monitor plaque-reducing treatments. Studies with longer follow-up periods will add more information on the carotid plaques’ development and accurately evaluate strain and shear wave indices’ predictive value.

**Conclusion**

Ultrasound elastography is a promising method for the assessment of atherosclerotic carotid plaques. It allows for the distinction of vulnerable carotid plaques in patients with or without cognitive disorders secondary to stroke. SWE indices seem to be more robust compared to strain elastography indices in identifying vulnerable carotid plaques. There is a need for more extensive and longer prospective controlled clinical studies to validate elastography as an imaging modality for detecting unstable carotid plaques with the potential to prevent and guide stroke treatment.

**Conflict of interest:** none

**References**

1. GBD 2016 Stroke Collaborators. Global, regional, and national burden of stroke, 1990–2016: a systematic analysis for the Global Burden of Disease Study 2016. Lancet Neurol 2019;18:439–458.
2. Flaherty ML, Kissela B, Khoury JC, et al. Carotid artery stenosis as a cause of stroke. Neuroepidemiology 2012;40:36–41.
3. Brinjikji W, Rabinstein AA, Lanzino G, et al. Ultrasound characteristics of symptomatic carotid plaques: A systematic review and meta-analysis. Cerebrovasc Dis 2015;40:165–174.
4. Coolen BF, Poot DHJ, Liem MI, et al. Three-dimensional quantitative T1 and T2 mapping of the carotid artery: Sequence design and in vivo feasibility. Magn Reson Med 2016;75:1008–1017.
5. Sidhu PS. Multiparametric Ultrasound (MPUS) Imaging: Terminology Describing the Many Aspects of Ultrasoundography. Ultraschall Med 2015;36:315–317.
6. Bamber J, Cosgrove D, Dietrich CF, et al. EFSUMB Guidelines and Recommendations on the Clinical Use of Ultrasound Elastography. Part 1: Basic Principles and Technology. Ultraschall Med 2013;34:169–184.
7. Hansen HHG, De Borst GJ, Bots ML, Moll FL, Pasterkamp G, De Korte CL. Validation of noninvasive in vivo compound ultrasound strain imaging using histologic plaque vulnerability features. Stroke 2016;47:2770–2775.
8. Sarvazyan AP, Rudenko OV, Swanson SD, Fowlkes JB, Emelianov SY. Shear wave elasticity imaging: A new ultra-
sonic technology of medical diagnostics. Ultrasound Med Biol 1998;24:1419–1435.
9. Chai CK, Akyildiz AC, Speelman L, et al. Local axial compressive mechanical properties of human carotid atherosclerotic plaques-characterisation by indentation test and inverse finite element analysis. J Biomech 2013;46:1759–1766.
10. Meairs S, Hennerici M. Four-dimensional ultrasonographic characterization of plaque surface motion in patients with symptomatic and asymptomatic carotid artery stenosis. Stroke 1999;30:1807–1813.
11. Muraki M, Mikami T, Yoshimoto T, et al. Sonographic Detection Of Abnormal Plaque Motion Of The Carotid Artery : Its Usefulness In Diagnosing High-Risk Lesions Ranging From Plaque Rupture To Ulcer Formation. Ultrasound Med Biol 2015;42:358-364.
12. Kume S, Hama S, Yamane K, Wada S, Nishida T, Kurisu K. Vulnerable carotid arterial plaque causing repeated ischemic stroke can be detected with B-mode ultrasonography as a mobile component: Jellyfish sign. Neurosurg Rev 2010;33:419–430.
13. Lee RT, Richardson SG, Loree HM, et al. Prediction of mechanical properties of human atherosclerotic tissue by high-frequency intravascular ultrasound imaging an in vitro study. Arterioscler Thromb 1992;12:1–5.
14. De Korte CL, Pasterkamp G, Van Der Steen AF, Woutman HA, Bom N. Characterization of plaque components with intravascular ultrasound elastography in human femoral and coronary arteries in vitro. Circulation 2000;102:617–623.
15. Bonnefous O, Brevannes L, Denis E, et al. New noninvasive echographic technique for arterial wall characterization. In: Radiology. Radiological Soc North Amer 20th And Northampton Sts, Easton, Pa 18042; 1996:129.
16. Kanai H, Hasegawa H, Ichiki M, Tetzuka F, Koika Y. Elasticity Imaging of Atheroma With Transcutaneous Ultrasound: : preliminary study. Circulation 2003;107:3018–3021.
17. de Korte CL, Hansen HHG, van der Steen AFW. Vascular ultrasound for atherosclerosis imaging. Interface Focus 2011;1:565–575.
18. Box LC, Angiolillo DJ, Suzuki N, et al. Heterogeneity of atherosclerotic plaque characteristics in human coronary artery disease: a three-dimensional intravascular ultrasound study. Catheter Cardiovasc Interv 2007;70:349–356.
19. Tarcqui P, Broisat A, Toczek J, Mesnier N, Ohayon J, Riou L. Mapping elasticity moduli of atherosclerotic plaque in situ via atomic force microscopy. J Struct Biol 2011;174:115–123.
20. Wang X, Jackson DC, Varghese T, et al. Correlation Of Cognitive Function With Ultrasound Strain Indices In Carotid Plaque. Ultrasound Med Biol 2014;40:78–89.
21. Wang X, Jackson DC, Mitchell CC, et al. Classification of Symptomatic and Asymptomatic Patients with and without Cognitive Decline Using Non-Invasive Carotid Plaque Strain Indices as Biomarkers. Ultrasound Med Biol 2016;42:909-918.
22. Cloutier G, Cardinal MR, Ju Y, Giroux MF, Lanthier S, Soulez G. Carotid Plaque Vulnerability Assessment Using Ultrasound Elastography and Echogenicity Analysis. AJR Am J Roentgenol 2018;211:847-855.
23. Wang X, Mitchell CC, Varghese T, et al. Improved Correlation Of Strain Indices with Cognitive Dysfunction with Inclusion of Adventitial Layer with Carotid Plaque. Ultrasound Imaging 2015;38:194-208.
24. Roy Cardinal MH, Heusinkveld MHG, Qin Z, et al. Carotid Artery Plaque Vulnerability Assessment Using Noninvasive Ultrasound Elastography: Validation With MRI. AJR Am J Roentgenol 2017;209:142–151.
25. Naim C, Cloutier G, Mercure E, et al. Characterisation of carotid plaques with ultrasound elastography : feasibility and correlation with high-resolution magnetic resonance imaging. Eur Radiol 2013;23:2030–2041.
26. Huang C, He Q, Huang M, et al. Non-Invasive Identification Of Vulnerable Atherosclerotic Plaques Using Texture Analysis In Ultrasound Carotid Elastography: An In Vivo Feasibility Study Validated By Magnetic Resonance Imaging. Ultrasound Med Biol 2017;43:817-830.
27. Huang C, Pan X, He Q, et al. Ultrasound-Based Carotid Elastography For Detection Of Vulnerable Atherosclerotic Plaques Validated By Magnetic Resonance Imaging. Ultrasound Med Biol 2016;42:365-377.
28. Liu Z, Bai Z, Huang C, et al. Interoperator Reproducibility of Carotid Elastography for Identification of Vulnerable Atherosclerotic Plaques. IEEE Trans Ultrasound FerroelectrFreq Control 2019;66:505–516.
29. Liu F, Yong Q, Zhang Q, Liu P, Yang Y. Real-time tissue elastography for the detection of vulnerable carotid plaques in patients undergoing endarterectomy. Ultrasound Med Biol 2015;41:705–712.
30. Hansen HHG, Borst GJ De, Bots ML, Moll FL, Pasterkamp G, Korte CL De. Ultrasound Strain Imaging Using Histologic Plaque Vulnerability Features. Stroke. 2016;(766).
31. Zhang Q, Li C, Zhou M, et al. Quantification of carotid plaque elasticity and intraplaque neovascularization using contrast-enhanced ultrasound and image registration-based elastography. Ultrasones [Internet]. 2015;1–10.
32. Lou Z, Yang J, Tang L, et al. Shear Wave Elastography Imaging for the Features of Symptomatic Carotid Plaques A Feasibility Study. J Ultrasound Med 2017;36:1213-1223.
33. Shang J, Wang W, Feng J, et al. Carotid Plaque Stiffness Measured with Supersonic Shear Imaging and Its Correlation with Serum Homocysteine Level in Ischemic Stroke Patients. Korean J Radiol 2018;19:15–22.
34. Rammarine KV, Garrard JW, Kanber B, Nduwayo S, Hartshorne TC, Robinson TG. Shear wave elastography imaging of carotid plaques: feasible, reproducible and of clinical of clinical potential. Cardiovasc Ultrasound 2014;12:49.
35. Marlevi D, Mulvagh SL, Huang R, et al. Combined spatiotemporal and frequency-dependent shear wave elastography enables detection of vulnerable carotid plaques as validated by MRI. Sci Rep 2020;10:403.
36. Doherty JR, Dahl JJ, Kranz PG, et al. Comparison of Acoustic Radiation Force Impulse Imaging Derived Carotid Plaque Stiffness with Spatially Registered MRI Determined Composition. IEEE Trans Med Imaging 2015;34:2354-2365.
37. Torres G, Czernuszewicz TJ, Homeister JW, et al. Delineation of Human Carotid Plaque Features In Vivo by Exploiting Displacement Variance. IEEE Trans Ultrason Ferroelectr Freq Control 2019;66:481-492.
38. Czernuszewicz TJ, Homeister JW, Caughey MC, et al. Performance of acoustic radiation force impulse ultrasound imaging for carotid plaque characterization with histologic validation. J Vasc Surg 2017;66:1749-1757.e3.
39. Garrard JW, Ummur P, Nduwayo S, et al. Shear Wave Elastography May Be Superior to Greyscale Median for the Identification of Carotid Plaque Vulnerability: A Comparison with Histology. Ultraschall Med 2015;36:386-390.
40. Di Leo N, Venturini L, de Socio L, Lucchetti VFP, Alagna GCG. Multiparametric ultrasound evaluation with CEUS and shear wave elastography for carotid plaque risk stratification. J Ultrasound 2018;21:293-300.
41. Falk E, Shah PK, Fuster V. Coronary Plaque Disruption. Circulation 1995;92:657–671.
42. Finn AV, Nakano M, Narula J, Kolodgie FD, Virmani R. Concept of vulnerable/unstable plaque. Arterioscler Thromb Vasc Biol 2010;30:1282–1292.
43. Ribbers H, Lopata RG, Holewijn S, Pasterkamp G, Blankensteijn JD, de Korte CL. Noninvasive two-dimensional strain imaging of arteries: validation in phantoms and preliminary experience in carotid arteries in vivo. Ultrasound Med Biol 2007;33:530–540.
44. Maurice RL, Olayon J, Fréteigny Y, Bertrand M, Soulez G, Cloutier G. Noninvasive vascular elastography: theoretical framework. IEEE Trans Med Imaging 2004;23:164–180.
45. Shi H, Mitchell CC, McCormick M, Kliewer MA, Dempsey RJ, Varghesse T. Preliminary in vivo atherosclerotic carotid plaque characterization using the accumulated axial strain and relative lateral shift strain indices. Phys Med Biol 2008;53:6377–6394.
46. Shapo BM, Crowe JR, Erkamp R, Emelianov SY, Eberle MJ, O’Donnell M. Strain imaging of coronary arteries with intraluminal ultrasound: experiments on an inhomogeneous phantom. Ultrason Imaging 1996;18:173–191.
47. de Korte CL, Carlier SG, Mastik F, et al. Morphological and mechanical information of coronary arteries obtained with intravascular elastography. Feasibility study in vivo. Eur Heart J 2002;23:405–413.