Observer performance in characterization of carotid plaque texture and surface characteristics with 3D versus 2D ultrasound

Sook Sam Leong a,*, Anushya Vijayananthana, Nur Adura Yaakupa, Nazri Shah a, Kwan Hoong Ng a, U. Rajendra Acharyab, c, d, Mehmet Bilgen e

a Department of Biomedical Imaging, University Malaya Medical Centre Kuala Lumpur, Malaysia
b Department of Electronics and Computer Engineering, Ngee Ann Polytechnic, Singapore
c Department of Biomedical Engineering, Faculty of Engineering, University of Malaya, Singapore
d Department of Biomedical Engineering, School of Science and Technology, SIM University, Singapore
e Department of Biophysics, University of Adnan Menderes, Aydin, Turkey

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ABSTRACT

Objective: To determine the reproducibility of three-dimensional (3D) ultrasound (US) over two-dimensional (2D) US in characterizing atherosclerotic carotid plaques using inter- and intra-observer agreement metrics.

Methods: A Total of 51 patients with 105 carotid artery plaques were screened using 3D and 2D US probes attached to the same US scanner. Two independent observers characterized the plaques based on the morphological features namely echotexture, echogenicity and surface characteristics. The scores assigned to each morphological feature were used to determine intra- and inter-observer performance. The level of agreement was measured using Kappa coefficient.

Results: The first observer with 2D US showed fair (k=0.4–0.59) and very strong (k>0.8) with 3D US intra-observer agreements using three morphological features. The second observer indicated moderate strong (k=0.6–0.79) with 2D US and very strong with 3D US (k>0.8) intra-observer performances. Moderate strong (k=0.6–0.79) and very strong (k>0.8) inter-observer agreements were reported with 2D US and 3D US respectively. The results with 2D and 3D US were correlated 62% using only echotexture and 56% using surface morphology coupled with echogenicity. 3D US gave a lower score than 2D 71% of the time (p=0.005) in disagreement cases.

Conclusion: High reproducibility in carotid plaque characterization was obtained using 3D US rather than 2D US. Hence, it can be a preferred imaging modality in routine or follow up plaque screening of patients with carotid artery disease.

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1. Introduction

Atherosclerosis of carotid artery is the main cause of ischemic stroke as certain plaques rupture and release its content to cause cerebral emboli [1,2]. Stroke occurs without warning; thus screening carotid artery for the detection of plaques which are vulnerable to rupture has considerable clinical importance and implications. Many studies have highlighted that stroke caused by carotid artery atherosclerosis is closely related to the degree of stenosis [3]. However, measuring the severity of stenosis solely is not adequately sensitive and specific biomarker for assessing the risk of stroke. The composition of plaque as well as the irregular surface morphology are the statistically significant contributors for the development of future neurological events leading to stroke [4,5]. Atherosclerotic plaques are divided into two broad categories: stable and unstable (also known as vulnerable). The texture of the plaque in general is characterized as homogeneous or heterogeneous (Fig. 1). Homogeneous plaques have uniform shade of gray echo pattern, smooth surface contour, and less symptomatic as they are more stable than soft plaques [6]. Heterogeneous plaques usually have more complex echo pattern and have at least one echolucent or hypoechoic area [7]. Heterogeneous and echolucent plaques are characterized as “unstable” or “soft” [8]. Thus, patients with homogeneous plaques are at lower risk of developing ischemic brain syndromes as compared to patients with echolucent and heterogeneous plaques [4]. The echogenicity of plaque is determined by its composition [10]. The hyperechoic uniform acoustic texture plaques usually correspond to pathologically fibrous, calcification or connective tissues [7]. Normally, calcified plaques are too dense and the resulting sound wave completely
gets reflected causing a black acoustic shadow behind them (Fig. 2a). An isoechoic plaque has the same echogenicity as normal intima media complex [11]. The echolucent areas within the plaque generally have lower calcium content corresponding to intraplaque hemorrhage, lipids, cholesterol, or loose proteinaceous deposit, which make them appear hypoechoic [9]. A mix echogenicity plaque is described as combination of hyperechoic, isoechoic and hypoechoic. In order to assess the echogenicity of the plaque, echogenicity of intima-media complex (IMT) around the plaque is used for comparison (Fig. 3).

The surface morphology plays an essential role in assessing the risk of ischemic stroke (Fig. 4). The surface can be ulcerated, irregular or smooth. Ulcerated or fissured plaques are caused by rupture of fibrous cap which exposes the thrombogenic material called collagen to the circulation and eventually resulting in thrombus formation in the lumen [5]. Irregular plaques have height difference between 0.4 and 2 mm which can be seen along the contour of the lesion [12]. In a population-based cohort, carotid plaque with irregular surface has three times more possibility of getting ischemic stroke than regular plaque surface [13]. Plaques with smooth border surface are characterized as simple or stable plaque [14]. It was reported that, the cumulative 5 years ischemic stroke risk among individuals with smooth plaque was less than 3% and more than 8% with irregular plaque [13]. High-resolution B

Fig. 1. US images showing echotexture of two different plaques (arrows): (a) homogeneous and (b) heterogeneous.

Fig. 2. US images showing echogenicity of four different plaques (arrows): (a) calcified, (b) isoechoic, (c) hypoechoic, and (d) mix echogenicity.
Mode ultrasonography is one of the best imaging modality and frequently used screening tool for direct visualization of the carotid arteries [14]. It provided better visualization and clinical advantage in the management of strokes. Traditionally, ultrasound (US) scans are performed with 2D probes, but more recently the trend is shifting towards using 3D probes [16]. The 2D US allows high resolution acquisitions, but the consistency of resulting images still depends on the user’s experience as the reconstruction of plaque shape and visualization of spatial relationships in the static image remains subjective [17]. Reproducibility need to be achieved as patients are scanned by different medical personal during each visit. The evaluation of carotid plaque size, surface irregularity and ulceration with 3D US are found to be feasible with better reproducibility than using 2D US [18–24]. But, the merits of 3D US in other aspects concerning the pathological features specific to plaque composition are yet to be established and requires further research [20,25]. Hence, in this study, we analyzed the observer performances to assess the consistency of identification and characterization of internal plaque composition using echotexture, echogenicity and surface characteristics with 3D US in clinical settings.

2. Materials and methods

The US scans of patients referred by physician for atherosclerosis evaluation were routinely carried out with 2D probe in our clinics at University of Malya Medical Center Biomedical Imaging Department, Malaysia. However, for this study, the sonographer (coauthor SSL) scanned the data using both 2D and 3D probes for all patients under the same imaging protocol in one month period. This practice provided consistency in evaluating the performance of carotid plaque detection. In the retrospective analysis as described below, we included the patients who have never undergone any US examination and no history of carotid artery disease but with clinical symptoms such as weakness of limb or face, blindness in one or both eyes or double vision without any constraints on age, gender or ethnic background. The patients with known history of carotid artery disease were excluded. A total of 105 carotid plaques from bilateral common carotid artery and internal carotid artery were taken from 51 (14 female and 37 male) patients with age between 40 and 92 years old (mean 69.1 ± 9.8 years) and degree of stenosis between 10–85% (mean 39.79) for this observer performance analysis. The ethnic composition comprised of Malay (n=11, 21.6%), Indian (n=12, 23.5%), Chinese (n=27, 52.9%) and other (n=1, 2.0%) origins. The US scans were performed using clinically approved high resolution Philips IU-22 Intelligent Ultrasound system using probes L9-3 MHz (2D linear array 160 element and 38 mm effective aperture length) and VL13-5 MHz (3D mechanical, high pitch, linear array with 192 elements). The carotid artery images were acquired bilaterally using first 2D and then 3D US probe with patient being in supine position. Common carotid artery (CCA), internal carotid artery (ICA), external carotid artery (ECA) and vertebral artery were assessed along the long (transducer in longitudinal orientation) and short axes (transducer in transverse orientation) projections on both sides. Once a plaque was detected and confirmed by a radiologist, sonographer captures 5 long axis and 5 short axis images of the plaque in 2D B-mode. The degree of stenosis and velocity of stenotic region was recorded. At the same location, volume data in B-mode from 9 slices with 1.7 mm distance in between in static mode, i.e., without moving the 3D probe was acquired.

The following US acquisition protocol was used to ensure optimum image quality:

Fig. 3. Structure referred (circle) as control for plaque echogenicity evaluation, plaque near wall (arrow) and plaque far wall (arrow head).

Fig. 4. US images showing surface morphologies of three different plaques (arrows): (a) ulcerated, (b) irregular and (c) smooth.
a. Tissue harmonic imaging was activated to improve the signal-to-noise ratio and reduce the image artifacts.
b. Maximum dynamic range was set to ensure larger range of grayscale.
c. Time gain compensation was arranged in a slopping curve through the tissue to ensure similar brightness levels for the adventitia of anterior and posterior walls.
d. Overall gain was adjusted to improve the image quality.
e. Depth was decreased to provide larger plaque image.
f. For the volume acquisition, parameters were set at tilt = 0°, frequency = 59 Hz, and resolution over speed option was selected.

2.1. Observer performance study

The 2D and 3D US datasets previously recorded by the sonographer (coauthor SSL) were filtered by the same coauthor according to the above described exclusion criteria. The remaining datasets were independently read by two observers (A and B) who have at least 5 years of clinical experience in radiology and US readings (coauthors AV, NAY). The observers characterized the carotid artery for atherosclerosis based on the criteria published in [26]. There is evidence to suggest that morphology of plaque may improve pre-existing risk stratification criteria [27]. Thus, individual plaque was characterized based on echotexture, echogenicity, and surface morphology and scoring values are shown in Table 1. Plaques with break on the surface and a significant wall at its base seen in two different planes were characterized as ulcerated. Plaques with height variation were characterized as irregular and smooth surface as smooth. The 2D images were analyzed directly by the observers on the picture archiving and communication system. But, the 3D US data sets were post processed and analyzed using manufacturer supplied quantification software QLAB (version 7.1, Philips Medical System, Seattle USA).

Each observer first evaluated the plaque characteristics of all patients using 2D images and then scored the 3D datasets. This practice ensured that observers remained blinded to the 2D images while evaluating 3D datasets from the same patient. The procedure was repeated for measuring the intra-observer performance. Hence, each radiologist read both 2D and 3D datasets and graded the plaques at two different instances in one month interval to reduce the recall bias in the readings. Next, to evaluate the inter-observer performance, each observer selected one of the two readings as final score for comparison.

2.2. Statistical analysis

The results of scores of echotexture, echogenicity and surface morphology features of plaques were analyzed statistically to determine the intra- and inter-observer performances. The level of agreements of scores were expressed using kappa coefficient and Wilcoxon Signed Rank test (SPSS 18.0). The kappa coefficient was used to evaluate the performance of the proposed work. The agreement between observers (Kappa coefficient) is considered strong, if $p < 0.005$.

3. Results

A total of 105 plaques were identified from 51 patients by the sonographer and characterized by two observers according to the scoring scheme shown in Table 1. Fig. 5 shows the typical plaques detected from the patients in this study. It is evident from the image that, 3D US produced higher quality with better spatial resolution carotid images than the 2D US (axial and lateral resolution for 2D and 3D were 0.6 mm, 0.8 mm, 0.5 mm and 0.5 mm respectively). Improvements in both image quality and resolution obtained with 3D probe have contributed to better spatial delineation of plaques and their surface morphologies are facilitated by visualization in multiple orthogonal planes (transverse and longitudinal) simultaneously. The advanced tools in QLAB workstation used for post processing of 3D datasets enabled the observers to have a closer look at the plaque with multiplanar reconstruction (MPR) and i-slice options available for volumetric rendering and slicing up volume in different slice thickness. In these views, unique properties of US signal patterns associated with echotexture and echogenicity accurately reflected the internal plaque composition.

Kappa coefficients obtained from statistical analysis of scores are summarized in Tables 2, 3. Kappa coefficients were statistically significant ($p < 0.005$). For both observers, the intra-observer performance showed very strong agreements with 3D US datasets with kappa coefficient more than 0.8 (Table 2). The reproducibility of characterizing the same plaque was fair for all features using 2D images for observer A ($k$ = 0.545, 0.562, 0.559) and moderately strong for observer B ($k$ = 0.723, 0.659, 0.776). The kappa coefficient indicated a very strong agreement ($k$ = 0.8) for 3D US images with moderately strong agreement for 2D US images ($k$ = 0.6 to 0.79). The level of inter and intra-observer agreement was substantial to almost perfect with 3D US ($k$ = 0.8–0.9). This clearly indicates that, almost similar reading were obtained from both observers for all criteria.

We have obtained 62% degree of agreement between 2D and 3D methods using echotexture feature. Among the cases they did not agree 85% of times, 3D US identified the plaques as homogeneous, and the rest (15%) as heterogeneous ($P < 0.001$) (Table 4). We gave a score of 1 for abnormal cases (irregular/ulcerated and non-calciﬁed, unstable plaque) and 0 for normal findings (smooth, calculated) using surface morphology and echogenicity. Summing these two variable scores yielded total between 0 and 2. A Wilcoxon signed rank test showed that 2D and 3D US correlated in 56% of cases. In the cases that they did not agree, 3D US method gave lower (less severe) score than 2D method for 71% of times. This finding was justified by low p value of 0.005 (Table 5).

4. Discussion

Stenosis is the narrowing of artery due to the plaque formation. Duplex US helps in reliable assessment of hemodynamic blood flow [28]. As the degree of stenosis increases (50–79%), the systolic velocity will be more than 120 cm/s [29]. At present, the standard operating procedure in the center involves only detecting carotid plaque and measuring the velocity of blood flow through the

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Scores used for characterize the carotid plaques based on echotexture, echogenicity and surface morphology features.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Echotexture</td>
<td>Echogenicity</td>
</tr>
<tr>
<td>Homogeneous</td>
<td>Heterogeneous</td>
</tr>
<tr>
<td>Score</td>
<td>1</td>
</tr>
</tbody>
</table>
narrowed section of artery using color Doppler sonography (CDS). The existing US scanners provide only 2D images from which these measurements are possible.

Consistent 3D datasets can be obtained by evaluating plaques in multiple planes simultaneously. The results shown in Tables 2 and 3 suggest that, the coefficients of echotexture, echogenicity and surface morphology evaluated using 3D US were relatively higher than obtained with 2D US. The scores given at two different instances by the same observer or separately by observers collectively indicated an excellent reproducibility of plaque characterizations and thus better intra- and inter observer performances with 3D US than using 2D US.

It is crucial to scan the plaques in both long axis (transducer in longitudinal orientation) and short axis (transducer in transverse orientation) planes to avoid false identification of sonolucents space between the plaque and wall[30]. Also, previous attempts to characterize carotid plaque with 2D US was not effective, as it revealed that 2D US was unable to estimate the volume of fibrosis or lipids within the plaque as the intra- and inter-observer agreement kappa was 0.44 and 0.38 respectively. [31].

In our current study, 2D US images were acquired both in long and short axes and plaque was reconstructed mentally. As a result,

Table 2
Kappa coefficients representing the levels of intra-observer agreement on the characterization of plaques.

<table>
<thead>
<tr>
<th>Types</th>
<th>Echotexture</th>
<th>Echogenicity</th>
<th>Surface morphology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observer A 2D</td>
<td>0.545 (95% CI, 0.42, 0.67)</td>
<td>0.562 (95% CI, 0.37, 0.76)</td>
<td>0.559 (95% CI, 0.42, 0.70)</td>
</tr>
<tr>
<td>p &lt; 0.005</td>
<td>p &lt; 0.005</td>
<td>p &lt; 0.005</td>
<td></td>
</tr>
<tr>
<td>3D</td>
<td>0.867 (95% CI, 0.77, 0.96)</td>
<td>0.815 (95% CI, 0.72, 0.91)</td>
<td>0.83 (95% CI, 0.83, 0.89)</td>
</tr>
<tr>
<td>p &lt; 0.005</td>
<td>p &lt; 0.005</td>
<td>p &lt; 0.005</td>
<td></td>
</tr>
<tr>
<td>Observer B 2D</td>
<td>0.723 (95% CI, 0.58, 0.86)</td>
<td>0.659 (95% CI, 0.77)</td>
<td>0.776 (95% CI, 0.66, 0.89)</td>
</tr>
<tr>
<td>p &lt; 0.005</td>
<td>p &lt; 0.005</td>
<td>p &lt; 0.005</td>
<td></td>
</tr>
<tr>
<td>3D</td>
<td>0.809 (95% CI, 0.70, 0.92)</td>
<td>0.822 (95% CI, 0.73, 0.91)</td>
<td>0.885 (95% CI, 0.79, 0.98)</td>
</tr>
<tr>
<td>p &lt; 0.005</td>
<td>p &lt; 0.005</td>
<td>p &lt; 0.005</td>
<td></td>
</tr>
</tbody>
</table>

Table 3
Kappa coefficients representing the levels of inter-observer agreement between the characterization of plaques.

<table>
<thead>
<tr>
<th>Types</th>
<th>Echotexture</th>
<th>Echogenicity</th>
<th>Surface morphology</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D</td>
<td>0.710 (95% CI, 0.55, 0.87)</td>
<td>0.633 (95% CI, 0.52, 0.75)</td>
<td>0.784 (95% CI, 0.67, 0.89)</td>
</tr>
<tr>
<td>p &lt; 0.005</td>
<td>p &lt; 0.005</td>
<td>p &lt; 0.005</td>
<td></td>
</tr>
<tr>
<td>3D</td>
<td>0.865 (95% CI, 0.77, 0.96)</td>
<td>0.851 (95% CI, 0.77, 0.93)</td>
<td>0.924 (95% CI, 0.85, 1.0)</td>
</tr>
<tr>
<td>p &lt; 0.005</td>
<td>p &lt; 0.005</td>
<td>p &lt; 0.005</td>
<td></td>
</tr>
</tbody>
</table>

Table 4
Wilcoxon Signed-rank Test comparing the degree of agreement in echotexture between 2D and 3D US methods.

<table>
<thead>
<tr>
<th>Echotexture_{A_3D} - echotexture_{A_2D}</th>
<th>N</th>
<th>Mean rank</th>
<th>Sum of ranks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Echotexture_{A_3D} - echotexture_{A_2D}</td>
<td>34</td>
<td>20.50</td>
<td>697.00</td>
</tr>
<tr>
<td>Echotexture_{A_3D} - echotexture_{A_2D}</td>
<td>6</td>
<td>20.50</td>
<td>123.00</td>
</tr>
<tr>
<td>Ties</td>
<td>65</td>
<td>Total</td>
<td>105</td>
</tr>
</tbody>
</table>

Test statistics

\[ Z = -4.427^- \]

Asymp. Sig. (2-tailed) 0.000

* Echotexture_{A\_3D} < echotexture_{A\_2D}: homogeneous.
* Echotexture_{A\_3D} > echotexture_{A\_2D}: heterogeneous.
* Echotexture_{A\_3D} = echotexture_{A\_2D}: agree.

* Wilcoxon Signed Ranks Test.
* Based on positive ranks.
observer agreements with 2D US was lower as compared to 3D US, but still better than previous findings. The previous study was conducted ten years ago and hence that equipment did not provide the image quality comparable to the modern advanced equipment. Another cause may be the use of less specific categories in previous studies. In our study, we developed six categories (echochotent, heterogeneous, and echogenic) were used [12,32]. Less precise categorization might have caused confusion to the observers while describing the carotid plaque.

The findings on surface morphology shown in Table 2 supports the previous findings and demonstrates the consistency in displaying plaque surface with 3D US [33]. Enhanced visualization of plaque surface and improved demarcation of vessel walls with 3D US may have facilitated the observers with better detection and characterization of plaque surface.

Based on the observer performance results, reproducibility of 3D ultrasound (US) appears to be better as compared to 2D US in characterizing atherosclerotic carotid plaques. However the study still has some limitations in terms of systematic and practical aspects. The 2D images were evaluated based on the selected preformatted static images, not based on raw dataset as in 3D scans. As a result, observers were not able to manipulate the image quality in order to obtain the best 2D images. This could have induced some biasness in scoring. Also, the results were obtained with only two observers and more observers may be needed to arrive at more conclusive results. The 3D US probe has large footprint as compared to 2D US probe. In practice, the scanning process becomes challenging if the patient has a shorter neck. This problem gets aggravated, if the position of the plaque is at ICA where the movement of the probe easily gets obstructed by an angle of mandible. As a result, sonographer has to apply more pressure in order to obtain optimum quality images. At the same time, this may cause discomfort to the patients. The use of 3D US may get restricted due to the presence of motion artifacts while swallowing, cardiac movement and respiration. Moreover, posterior shadowing due to calcified plaque occurs occasionally in significant stenosis cases and makes the plaque identification especially ulceration more complicated [34,35]. Limited experience and prior training on the usage of 3D US probe can affect the workflow. The skill to analyze the data with many algorithms and different perspectives slows down the image interpretation. Extra time need to be spent on choosing the most appropriate algorithms and view the images. In addition, large volume of data produced by 3D US slows down the performance of workstation. Hence even experienced radiologists may need to spend more time to analyze the 3D data.

5. Conclusion

Reproducibility of carotid artery plaque characterization is higher with 3D US than static 2D US. 3D US enhances both intra and inter-observer performances in plaque characterization using echotexture, echogenicity and surface morphology features. Our findings can help to improve the diagnosis of atherosclerosis severity from carotid artery. However, it is too early to conclude that 3D US is the preferred choice for routine carotid screening or follow up of patients with known carotid artery disease or determine the efficacy of therapies for atherosclerosis. Our current findings are to be tested with huge database from different ethnic groups with more number of independent observers.

Conflict of interest

Not declared.

References