Original Article

Superb microvascular imaging for evaluation of microvascularity in breast nodules compared with conventional Doppler imaging

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Background: Neovascularity visualization in breast nodules is challenging due to the limitations of conventional Doppler imaging methods. This study aims to assess the performance of superb microvascular imaging (SMI) in evaluating the microvascularity of breast nodules (diameter ≤2 cm). The comparison of performances of SMI with color Doppler flow imaging (CDFI) and power Doppler imaging (PDI) was made by using a three-factor scoring system of vascularity. This study also investigated the common features of microvascularity in small malignant nodules on SMI for early differentiating from benign nodules.

Methods: Ninety-one female patients (with 125 breast nodules) were enrolled in this retrospective study. All the breast nodules were examined by grayscale ultrasonography (US), CDFI, PDI, and SMI. The number, morphologic features, and distribution of blood vessels were scored to evaluate the nodular vascularity in light of the three-factor scoring system. The diagnostic value of SMI for microvascularity in breast nodules was analyzed and compared with CDFI and PDI.

Results: Histological analysis showed 53 malignant and 72 benign nodules. The vascularity grades detected by SMI were significantly different from those of CDFI and PDI ($P<0.05$). SMI detected 47 grade-IV nodules of the total 125 nodules (37.6%), which was more than those detected by CDFI (10.4%, 13/125) and PDI (12.8%, 16/125), while more grade-I nodules were detected by CDFI (42.4%, 53/125) and PDI (36.8%, 46/125) compared with SMI (21.6%, 27/125). Differences in the vessel number, morphologic features, and distribution between benign and malignant breast nodules were significant on SMI ($P<0.05$). The vessel number ≥6, penetrating vessels, and a mixed distribution of vessels in peripheral and central nodular tissues were the common features of microvascularity in the grade-IV malignant nodules on SMI, whereas the blood vessels in the benign nodules were straight and branching and peripherally distributed.

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Conclusions: In comparison with CDFI and PDI, SMI enhances microvascularity detection, depicts the microvascular architecture in breast nodules and has potential in the differential diagnosis of malignant nodules from benign nodules.

Keywords: Breast nodules; superb microvascular imaging (SMI); microvascularity; malignancy estimation

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Introduction

The incidence of breast cancer has been increasing, and it has become one of the most common malignant tumors in women. It is shown that approximately one in 8 to 10 women suffers from breast cancer in her lifetime (1). Angiogenesis is crucial in the growth of malignant tumors including breast cancer. It has been found that the development, invasion, and survival of breast cancer are highly dependent on angiogenesis (2,3). The larger the volume of breast tumor is, the more Ki-67 is expressed and the more neovascularization occurs (4). The vascularity in the lesion could be used as an indicator of malignant nodule. According to Tumor Node Metastasis (TNM) classification of malignant tumors, it is successively expressed by T1 to T4 stage as the tumor volume increases. The breast tumors with a maximum diameter ≤2 cm are categorized as small tumors at the T1 stage (5). However, it is challenging to visualize the early neovascularization in these T1-stage small breast nodules (6).

Intratumoral vessels are usually examined by ultrasound techniques including color Doppler flow imaging (CDFI), power Doppler imaging (PDI), contrast-enhanced ultrasound (CEUS), and superb microvascular imaging (SMI). CDFI cannot display microvessels with a low flow rate. PDI is susceptible to interfere with non-blood flow information, and contrast agents used by CEUS require administration into the patient and involve additional costs (7,8). Compared with those techniques, SMI without the use of contrast agents is a novel imaging technique for better displaying microvessels where the blood flow is at low speed (9). Zhao *et al.* analyzed the vascular distributions and grade by CDFI and SMI (10). The size of the masses was 0.8–8.2 cm, with an average size of 2.91±1.08 cm in that study. Chae *et al.* evaluated the vascularity index (VI) on SMI of 11–47 mm hypoechoic masses (11). Their results demonstrated that SMI combined with grayscale ultrasonography (US) showed better diagnosis of malignant and benign breast tumors compared with grayscale US alone. Arslan *et al.* detected 90 lesions with a diameter of 21.89±17.12 mm on SMI (12). They found that the VI values of the malignant lesions were significantly higher than those of normal breast tissue (P<0.05), whereas the VI values of the benign breast lesions did not alter much. Park *et al.* applied a three-factor system to evaluate breast tumor vascularity on SMI in comparison with CDFI and PDI (13). They found that SMI showed higher vascular scores than CDFI and PDI and higher scores for malignant masses than benign masses. However, little attention has been paid to the accuracy of grayscale US, CDFI, PDI and SMI in early detection of smaller breast nodules with a limited size.

Therefore, this study focused on the T1-stage small breast nodules and applied SMI to detect microvessels with a low flow velocity in these nodules. The aims of this study are to assess the performance of SMI in evaluating the microvascularity of breast nodules (diameter ≤2 cm) in comparison with CDFI and PDI by the three-factor scoring system of vascularity (13), and to investigate the common features of microvascularity in small malignant nodules on SMI for early differentiating from benign nodules.

Methods

Patients

The inclusion criteria of this study were (I) female patients with breast nodules examined by ultrasound in grayscale US, CDFI, PDI, and SMI mode, (II) the breast nodules with a dimension equal to or less than 2 cm, and (III) neither radiotherapy nor chemotherapy performed before ultrasound examination. A total of 125 breast nodules (dimension ≤2 cm) from 91 female patients (mean age, 45.7±11.6 years old; range, 21–72 years) were collected from November 2018 to September 2019 in this retrospective study. All the breast nodules were confirmed by pathologic analysis after surgery or biopsy. The study was conducted in

Table 1 The three-factor scoring system used in this study

Factor scoring system	Score
Vessel number	
No vessels	0
1 vessel	1
2 vessels	2
3 vessels	3
4 vessels	4
5 vessels	5
≥6 vessels	6
Morphological complexity	
No vessels	0
Punctate vessels	1
Linear vessels	2
Branching vessels	3
Penetrating vessels	4
Vascular distribution	
Non-flow	0
Peripheral distribution	1
Central distribution	2
Mixed distribution	3

accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by the Institutional Ethics Committee of the Second Affiliated Hospital of Shandong First Medical University. Informed consent was provided by all the participants.

Ultrasound device and examination protocol

The bilateral breasts and armpits of all the patients in the supine position were scanned in grayscale US, CDFI, PDI, and SMI modes, respectively, by an ultrasonic diagnostic system (Aplio 500, Toshiba Corporation, Japan) equipped with a 14 MHz high-frequency linear array probe and an operation software. On two-dimensional grayscale US examination, the location, size, echogenicity, shape, contour features, aspect ratio, and calcification of the nodules were evaluated.

Then, the nodule and its surroundings in a range of approximately 1 cm were selected in a sampling window. In the CDFI mode, the vascular images of the entire nodule mass showing the most abundant blood flow and a video clip of the blood flow were recorded for analysis of blood flow characteristics. With the probe unmoved, the blood flow in the nodule in the same sampling window was recorded respectively in PDI and SMI modes. SMI was operated in two modes, i.e., color mode (cSMI) and monochrome mode (mSMI). cSMI displays a fused image which combines conventional grayscale ultrasound image with a color-encoded Doppler signals, while mSMI displays only the blood flow signals by subtracting away the background. In this study, both mSMI and cSMI were applied to evaluate the microvascularity of the nodules and a higher vascularity grade would be the SMI evaluation result for the performance analysis.

During Doppler imaging, the color gain was adjusted to display small vessels without artifacts, and pressurization was avoided on the nodule. In order to obtain the best image, each patient was asked to hold breath during ultrasound scanning. Three breast radiologists with more than 5 years' experience in breast ultrasound were involved in the study. One did the breast ultrasound examination and the other two performed image analysis.

Image analysis

After the characteristics of each breast nodule in the grayscale US images were extracted, the blood vessels in CDFI, PDI, and SMI images were scored according to the three-factor scoring system (13), which shed light on the vessel number in breast nodules, the complexity of vascular morphology, and vascular distribution (*Table 1*). The final vascular score for each nodule, therefore, was defined as the sum of the scores of the vessel number, morphologic feature, and vascular distribution ranging from 0 to 13. In this study, the microvascularity was evaluated by the two radiologists and then the final score was derived from the average which was rounded up or down in cases of disagreement. Finally, the microvascularity of all the nodules in CDFI, PDI, and SMI images were graded by the use of a five-grade grading method, which categorized microvascularity into 5 grades based on the vascular score (*Table 2*).

Statistical analyses

All statistical analysis was performed using SPSS software (version 24.0). χ^2 test and Fisher's exact test were used to analyze the statistical differences in the grayscale

Table 2 The five-grade grading system used in this study

The sum of scores	Grade
0–2	0
3–5	I
6–8	II
9–11	III
12–13	IV

Table 3 Pathological findings of 125 breast nodules

Breast nodules	Number
Malignant nodules (n=53)	
Invasive ductal carcinoma	37
Invasive breast carcinoma	4
Mucinous carcinoma	2
Medullary carcinoma	2
High-grade intraductal carcinoma	2
Invasive micropapillary carcinoma	2
Invasive adenocarcinoma	1
Intraductal papillary carcinoma	1
Ductal carcinoma in situ	2
Benign nodules (n=72)	
Fibroadenoma	55
Intraductal papilloma	8
Mammary adenosis	6
Inflammatory reaction focus	3

sonographic features. Wilcoxon rank-sum test was used to statistically analyze the differences in vascularity grades evaluated by SMI from CDFI and PDI and also in the SMI-detected vascular characteristics of benign and malignant nodules. Significant differences were accepted with P<0.05.

Results

Pathological results

The pathological analysis of the 125 breast nodules showed 53 malignant nodules and 72 benign nodules. The majority of malignant nodules were invasive ductal carcinomas (n=37, 69.8%). Fibroadenomas (n=55, 76.4%) constituted the majority of benign nodules. The details of the type and number of breast nodules are listed in *Table 3*. According to the pathological results, the nodules were divided into two groups, the malignant group, and the benign group.

Grayscale ultrasound appearances of 125 breast nodules

The patients with 53 malignant breast nodules (mean age: 51.96±8.88 years) were 10 years significantly senior to the patients with 72 benign breast nodules (mean age: 41.15±11.40 years) (P<0.05, *Table 4*). The specific manifestations of grayscale US of benign and malignant breast nodules are shown in *Table 4*. The statistically significant differences (P<0.05) were found between benign and malignant breast nodules in the number of breast nodules, nodular shape, aspect ratio, edge, posterior acoustic property, and calcification. There were no statistically significant differences (P>0.05) between benign and malignant breast nodules in nodule location, echogenicity, and ductal dilatation.

Evaluation of vascularity by SMI compared with CDFI and PDI

The vascularity of all the breast nodules in CDFI, PDI, and SMI images was graded (*Table 5*). It was found that the vascularity grade detected by SMI was significantly higher than that of CDFI and PDI (P<0.05). No significant difference was detected between CDFI and PDI (P=0.225). SMI detected more grade-IV nodules (37.6%, 47/125) than CDFI (10.4%, 13/125) and PDI (12.8%, 16/125). There were more grade-I nodules detected by CDFI (42.4%, 53/125) and PDI (36.8%, 46/125) than that of SMI (21.6%, 27/125). Furthermore, this study defined the detection rate of the blood flow as the number of the nodules with grade >0 over the total number of the nodules. The SMI detection rate (94.4%, 118/125) was highest in comparison with CDFI (87.2%, 109/125) and PDI (89.6%, 112/125).

Figures 1,2 show the typical images of malignant breast nodule by grayscale US, CDFI, PDI, mSMI, and cSMI. *Figure 1* indicates high vascularity of invasive ductal carcinoma. In comparison with CDFI, PDI, and cSMI, mSMI was able to demonstrate more details of microvessels. The angiogenesis in the nodule on mSMI was evaluated higher as grade IV (total score 13, >6 penetrating vessels with mixed distribution) than the grade III on CDFI (total score 10, 5 vessels with linear flow and mixed distribution), PDI and cSMI (total score 11, >6 vessels with similar

Table 4 Age of patients and grayscale ultrasound representation of 125 mammary nodules

Features	Benign nodules (n=72)	Malignant nodules (n=53)	P
Age (years) (mean ± standard deviation)	41.15±11.40	51.96±8.88	<0.05
Nodule location			0.917
Left	42	32	
Right	30	21	
Number of nodules			<0.05
Single	27	48	
Multiple	45	5	
Nodular shape			<0.05
Round/oval	39	3	
Irregular shape	33	50	
Aspect ratio			<0.05
≤1	71	42	
>1	1	11	
Edge			<0.05
Complete	67	6	
Incomplete	5	47	
Echogenicity			0.499
Hypoechogenicity	67	48	
Hyperechogenicity/isoecho	2	2	
Mixed echo	3	3	
Rear features			<0.05
No	64	30	
Augmentation	2	8	
Attenuation	6	15	
Calcification			<0.05
Yes	8	39	
No	64	14	
Ductal dilatation			0.237
Yes	6	1	
No	66	52	

vascular appearance to CDFI). *Figure 2* is another case of invasive ductal carcinoma. The evaluation of vascularity on mSMI has a higher grade (grade III, total score 10) compared with CDFI (grade II, total score 8), PDI (grade II, total score 6), and cSMI (grade II, total score 7).

Figures 3-5 indicate the low microvascularity of benign breast nodule. *Figure 3* shows a fibroadenoma on mSMI assessed as grade II with a total score of 6, whereas a lower microvascularity of grade I (total score 3) was evaluated on cSMI and no microvascularity (grade 0, total score 0) on CDFI and PDI. In *Figure 4*, an intraductal papilloma on mSMI, cSMI, CDFI, and PDI was assessed as grade I, but

Table 5 Comparison of the grading results examined by CDFI, PDI, and SMI

Vascularity grade	CDFI	PDI	SMI	P		
				CDFI *vs.* SMI	PDI *vs.* SMI	CDFI *vs.* PDI
0	16 (12.8)	13 (10.4)	7 (5.6)	<0.05	<0.05	0.225
I	53 (42.4)	46 (36.8)	27 (21.6)			
II	24 (19.2)	28 (22.4)	26 (20.8)			
III	19 (15.2)	22 (17.6)	18 (14.4)			
IV	13 (10.4)	16 (12.8)	47 (37.6)			

Data are shown as n (%). CDFI, color Doppler flow imaging; PDI, power Doppler imaging; SMI, superb microvascular imaging.

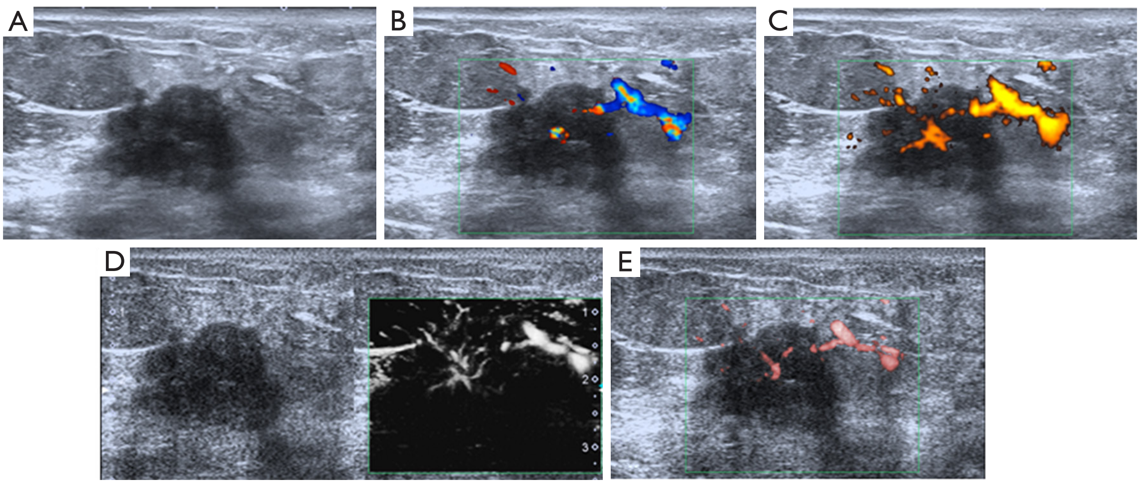

Figure 1 Typical grayscale US, CDFI, PDI, mSMI, and cSMI images of an invasive ductal carcinoma in the left breast of a 51-year-old patient. In the nodule, (A) grayscale US image shows a hypoechoic mass, (B) CDFI image shows 5 linear vessels with mixed distribution (total score 10, grade III), (C,E) PDI and cSMI images show >6 linear vessels with mixed distribution (total score 11, grade III), (D) mSMI image shows more detailed penetrating vessels (>6) with mixed distribution (total score 13, grade IV). US, ultrasonography; CDFI, color Doppler flow imaging; PDI, power Doppler imaging; mSMI, monochrome mode of superb microvascular imaging; cSMI, color mode of superb microvascular imaging.

the vascularity evaluation of mSMI had the highest score 5. *Figure 5* shows no angiogenesis in a single fibroadenoma with adenopathy assessed as grade 0 by all imaging methods.

These results indicated a better performance of SMI for the microvascularity of small malignant breast nodules than CDFI and PDI. Due to the lack of features of microvessels in CDFI and PDI images, malignant nodule might be graded with a lower vascular grade in CDFI and PDI images, which may induce a missed diagnosis of malignancy.

Differential diagnosis of malignant nodules by SMI

The number, morphology, and distribution scores of the blood vessels in malignant breast nodules were different from those of benign breast nodules examined by SMI (*Tables 6-8*). The number of blood vessels in benign and malignant nodules was significantly different (P<0.05, *Table 6*). There were more than 6 vessels observed in 36 of 53 (67.9%) malignant nodules, while only 10 of 72 benign nodules (13.9%) were found with more than 6 vessels.

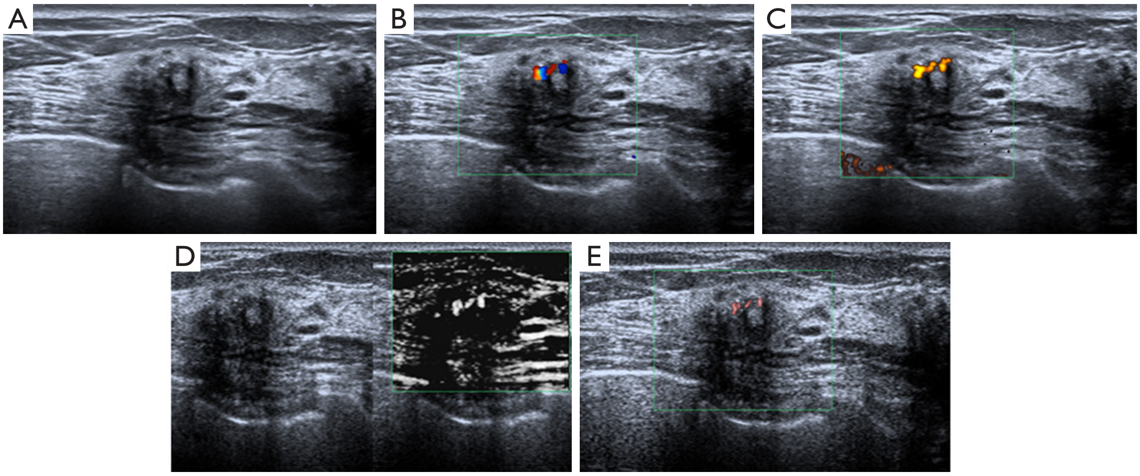

Figure 2 Typical grayscale US, CDFI, PDI, mSMI, and cSMI images of an invasive ductal carcinoma in the left breast of a 48-year-old patient. In the nodule, (A) grayscale US image shows a hypoechoic mass, (B) CDFI image shows 5 vessels with linear flow and peripheral distribution (total score 8, grade II), (C) PDI image shows 2 branching vessels with peripheral distribution (total score 6, grade II), (D) mSMI image shows 5 linear vessels with mixed distribution (total score 10, grade III), (E) cSMI image shows 4 linear vessels with peripheral distribution (total score 7, grade II). US, ultrasonography; CDFI, color Doppler flow imaging; PDI, power Doppler imaging; mSMI, monochrome mode of superb microvascular imaging; cSMI, color mode of superb microvascular imaging.

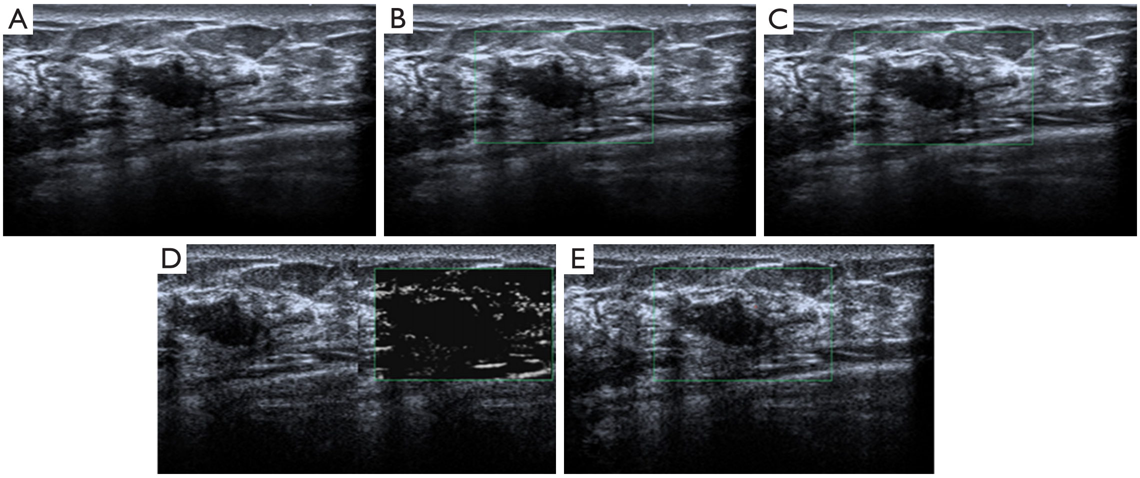

Figure 3 Typical grayscale US, CDFI, PDI, mSMI, and cSMI images of a single fibroadenoma in the right breast of a 46-year-old patient. In the nodule, (A) grayscale US image shows a hypoechoic mass, (B,C) CDFI and PDI images show no vessels (total score 0, grade 0), (D) mSMI image shows 3 linear vessels with peripheral distribution (total score 6, grade II), (E) cSMI image shows 1 punctate vessel peripherally distributed (total score 3, grade I). US, ultrasonography; CDFI, color Doppler flow imaging; PDI, power Doppler imaging; mSMI, monochrome mode of superb microvascular imaging; cSMI, color mode of superb microvascular imaging.

Usually, less than 3 vessels are developed in the benign nodules.

Differences in the morphologic features of vessels between benign and malignant nodules were statistically significant (P<0.05, *Table 7*). Penetrating vessels were found in the majority of malignant nodules with score 4 (33/53, 62.3%), whereas linear and branching vessels were mainly observed in benign nodules with score 2 (28/72, 38.9%) and score 3 (30/72, 41.7%).

The distribution features of vessels between benign and

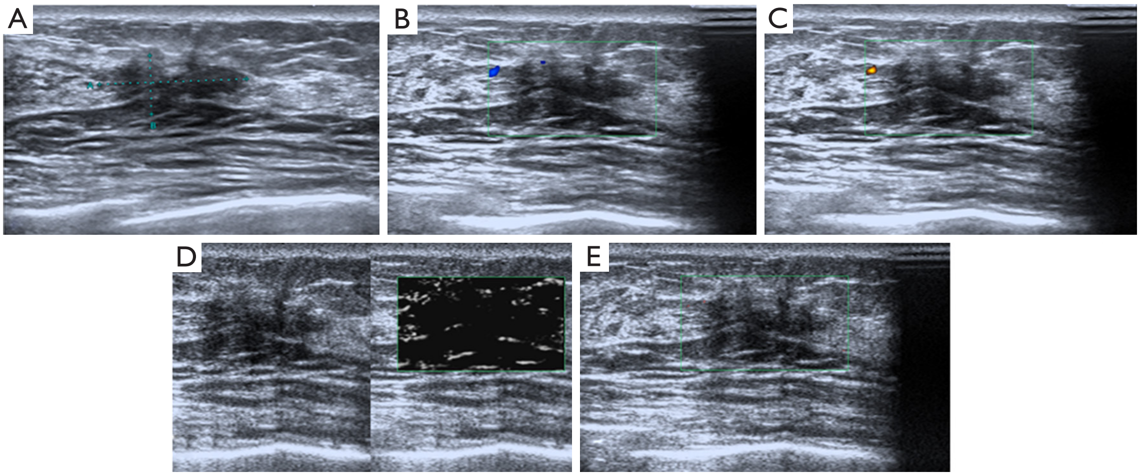

Figure 4 Typical grayscale US, CDFI, PDI, mSMI, and cSMI images of an intraductal papilloma in the left breast of a 44-year-old patient. In the nodule, (A) grayscale US image shows a hypoechoic mass in the nodule, (B,E) CDFI and cSMI images show 2 punctate vessels with peripheral distribution (total score 4, grade I), (C) PDI image shows 1 peripherally distributed punctate vessel (total score 3, grade I), (D) mSMI image shows 2 linear vessels with peripheral distribution (total score 5, grade I). US, ultrasonography; CDFI, color Doppler flow imaging; PDI, power Doppler imaging; mSMI, monochrome mode of superb microvascular imaging; cSMI, color mode of superb microvascular imaging.

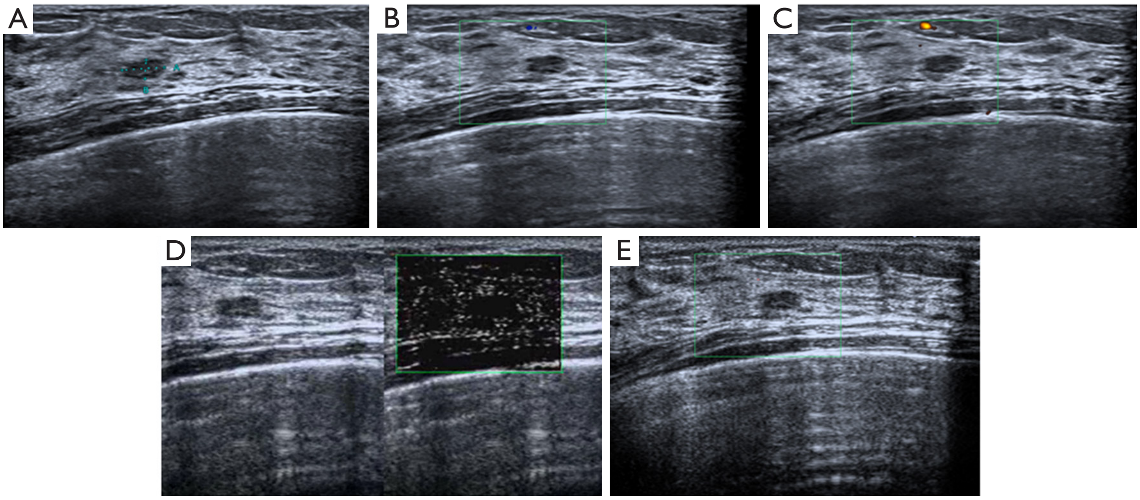

Figure 5 Typical grayscale US, CDFI, PDI, mSMI, and cSMI images of a fibroadenoma with adenopathy in the left breast of a 30-year-old patient. In the nodule, (A) grayscale US image shows a hypoechoic mass in the nodule, (B-E) CDFI, PDI, mSMI, and cSMI images show no vessels (total score 0, grade 0). US, ultrasonography; CDFI, color Doppler flow imaging; PDI, power Doppler imaging; mSMI, monochrome mode of superb microvascular imaging; cSMI, color mode of superb microvascular imaging.

malignant nodules were significantly different (P<0.05, *Table 8*). In 47 of 53 malignant nodules (88.7%), the blood vessels were usually distributed in both the peripheral and central regions, whereas the blood vessels were peripherally distributed in the majority of benign breast nodules (52.8%, 38/72).

Discussion

At present, the vascularization in tumors can be examined

Table 6 The number of the breast nodules with different scores of the number of blood vessels observed by SMI

Breast nodules	Score of the number of blood vessels							P
	0	1	2	3	4	5	6	
Benign nodules (n=72)	7 (9.7)	20 (27.8)	11 (15.3)	13 (18.1)	9 (12.5)	2 (2.8)	10 (13.9)	<0.05
Malignant nodules (n=53)	1 (1.9)	2 (3.8)	4 (7.5)	2 (3.8)	6 (11.3)	2 (3.8)	36 (67.9)	

Data are shown as n (%). SMI, superb microvascular imaging.

Table 7 The number of the breast nodules with different scores of vascular morphology observed by SMI

Breast nodules	Score of vascular morphology					P
	0	1	2	3	4	
Benign nodules (n=72)	7 (9.7)	6 (8.3)	28 (38.9)	30 (41.7)	1 (1.4)	<0.05
Malignant nodules (n=53)	1 (1.9)	1 (1.9)	2 (3.8)	16 (30.2)	33 (62.3)	

Data are shown as n (%). SMI, superb microvascular imaging.

Table 8 The number of the breast nodules with different scores of distribution of blood vessels observed by SMI

Breast nodules	Score of distribution of blood vessels				P
	0	1	2	3	
Benign nodules (n=72)	7 (9.7)	38 (52.8)	6 (8.3)	21 (29.2)	<0.05
Malignant nodules (n=53)	1 (1.9)	3 (5.7)	2 (3.8)	47 (88.7)	

Data are shown as n (%). SMI, superb microvascular imaging.

by SMI or the conventional Doppler methods such as CDFI and PDI. CDFI applies a wall filter of motion target indication to differentiate the flow from the motion artifacts, thus CDFI is able to provide vascularization in tumors. However, CDFI has limitations such as the loss of low-speed flow, angle dependence, and low signal-to-noise ratio (SNR) (14). Compared with CDFI, PDI has a wider range of blood flow velocity. It however is susceptible to interfere by non-blood flow information. The limitation in detecting blood flow in breast tumors by PDI was reported (15). Different from the single-dimensional filter of CDFI, SMI adopts a multi-dimensional filter to eliminate the clutter and motion artifacts to improve the visualization of blood flow. Therefore, SMI has an ability to detect microvessels (diameter ≤100 μm) with a low flow velocity (≤0.1 cm/s) (16), which compensates the shortcoming of CDFI being unable to show vessels with low flow velocities (3–5 cm/s) and small vessel diameters (diameter ≤2 mm) (6,15).

A previous study reported that mSMI might clearly display the morphology and distribution of vessels in breast lesions without the background (14). This study applied both cSMI and mSMI to examine the microvascularity in small breast nodules and found that mSMI image usually showed clearer vessels in number, morphology, and distribution. Althought the microvascularity on mSMI might be evaluated with a higher socre than that of cSMI, no significant difference was found between mSMI and cSMI evaluation.

Previous studies usually applied one parameter of VI to evaluate the malignancy and benignancy (11,12,17). However, VI is a Doppler parameter that is automatically determined by SMI to quantify flow signals as the ratio of color pixels to all pixels within the mass (11). In this study, we examined the microvascularity of small breast nodules not only by cSMI but also with mSMI. In mSMI image, there is no color pixels representing blood flow. Therefore, VI is improper for vascularity evaluation in this study. Park *et al.* applied a three-factor scoring system to evaluate vascularity of breast tumors according to the number of vessels, vessel morphology, and vascular distribution inside the tumors, which demonstrated a comprehensive evaluation of vascularity in tumors by the three-factor scoring system (13). This study therefore assessed the blood vessels in CDFI, PDI, and SMI images according to the three-factor scoring system instead of VI, extracted the common features of microvascularity in small breast nodules, and then graded the vascularity of the nodules by the five-grade grading system based on the final score of the comprehensive evaluation. SMI, especially mSMI, could quickly detect hyper vascularisation (18). The results of this study showed that mSMI could more clearly depict the blood vessels inside small breast nodules and consequently obtained a higher blood vessel detection rate and a higher percentage of the grade-IV nodules than CDFI and PDI.

This study also applied SMI to observe the differences in appearance of microvascularity between benign and malignant breast nodules. In general, there are two stages during tumor growth, the slow growth stage and the rapid proliferation stage. The growth rate of tumors is slow during the slow growth stage, but in the rapid proliferation stage, tumors grow fast after rich microangiogenesis which promotes rapid growth of tumors (19). Therefore, the evaluation of microangiogenesis in breast lesions is important to differentiate malignant from benign lesions (20). The characteristics of neovascularization in malignant breast nodules usually include large quantity, thin wall, disorganized tortuosity, and formation of arteriovenous fistula (21,22). This study revealed that the malignant nodules usually had a larger number of blood vessels (≥6) and those blood vessels were distorted, disordered, and radially distributed within both peripheral and central regions of the nodules. On the contrary, most benign nodules showed different vascularity, 1–3 vessels with regular and natural shape and mostly distributed in the periphery.

Previous studies demonstrated that SMI could be a promising ultrasound imaging mode to improve the differentiation of malignant and benign breast lesions because of its superiority in imaging microvascular structures in breast lesions (12,23). Taking advantages of SMI, this study extracted the common features of microvascularity in small malignant nodules, which benefits the detection of small malignant breast nodules with fewer missed diagnosis.

Conclusions

This study investigated the performance of SMI for the microvascularity of small breast nodules with a limited size ≤2 cm using the three-factor scoring system. In comparison with CDFI and PDI, SMI was usually effective in extracting small malignant nodules graded IV with the common features of microvascularity including the vessel number ≥6, penetrating vessels, and mixed distribution in peripheral and central nodular tissues. This study demonstrated that SMI is able to provide a higher grading of microvessels and a better performance on the detection of small malignant breast nodules.

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Footnote

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at https://qims.amegroups.com/article/view/10.21037/qims-23-136/coif). The authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by the Institutional Ethics Committee of the Second Affiliated Hospital of Shandong First Medical University. Informed consent was provided by all participants.

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