Review paper

Cite as: Babington EA, Amedu C, Anyasor E, Reeve R: Non-contrast ultrasound assessment of blood flow in clinical practice. J Ultrason 2024; 24: 29. doi: 10.15557/JoU.2024.0029.

Submitted: 15.01.2024
Accepted: 26.03.2024
Published: 18.09.2024

Non-contrast ultrasound assessment of blood flow in clinical practice

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DOI: 10.15557/JoU.2024.0029

Keywords
Doppler imaging; B-flow imaging; microvascular imaging; advanced dynamic flow

Abstract

Since the first clinical use of ultrasound in the 1940s, significant advancements have been made in its applications. Color Doppler imaging and power Doppler imaging are considered the first and second generations of flow ultrasound assessment tools, respectively. Subsequently, the introduction of contrast-enhanced ultrasound has significantly improved the assessment of arterial and venous vascular patterns in lesions and vessels. 'Blood flow brightness-mode imaging' or 'B-flow', a non-Doppler ultrasound flow assessment mode introduced more recently, provides even more information for ultrasound users in flow assessment. Microvascular imaging, introduced about a decade ago, is the third generation of Doppler non-contrast ultrasound flow modes, and is growing in popularity. Using a special wall filter, microvascular imaging overcomes the limitations of color Doppler imaging and power Doppler imaging in the detection of slow flowing signals. Advanced dynamic flow is a third-generation non-contrast Doppler flow technology that has so far gained popularity in obstetric ultrasound, commonly used to evaluate fetal umbilical vessels and heart chambers. This review article presents some recent updates on the various non-contrast ultrasound flow modalities available in clinical practice. It focuses on the design principles of individual flow modalities, discussing their strengths, limitations, and clinical applications, along with a review of the relevant literature.

Introduction

Ultrasound was first reportedly used for clinical purposes in the 1940s to investigate the brain[(1)]. Since then, there have been significant advancements in the applications of this medical imaging modality across various specialties for different anatomical organs. Blood circulation is essential for the function of normal body tissues[(2)]. Similarly, abnormal growths depend on blood supply and oxygenation for their development. This leads to the formation of unique circulatory network from the surrounding blood vessels, popularly known as neoangiogenesis[(2)].

Ultrasound in well-trained hands is a non-invasive, relatively inexpensive modality that can provide valuable real-time information on blood flow within the large and small vessels[(3)]. There are many different uses of ultrasound when assessing blood flow. Color Doppler imaging (CDI) and power Doppler imaging (PDI) are considered the first and second generations of flow ultrasound assessment tools, respectively[(4)].

Following CDI and PDI, the introduction of contrast-enhanced ultrasound (CEUS) has further improved the assessment of vascular patterns in lesions and flow in vessels[(5)]. CEUS utilizes the intravenous administration of microbubble-based contrast agents[(6)] into the bloodstream. Using a specific software package, microscopic vascularities are detectable at a specified time interval relative to the examined region[(5,6)]. This is similar to the phenomenon used in Contrast-Enhanced CT (CECT)/MRI which also relies on the intravenous introduction of contrast agents to visualize vessels and vascular areas[(7)]. Nevertheless, unlike CECT, CEUS poses a significantly lower risk of nephrotoxicity and is considered relatively safe for use[(7)]. Similar to CECT and MRI, CEUS is minimally invasive, requiring additional training from ultrasound users. Despite the advantages, the application of CEUS has not

yet reached acceptance globally, as initially anticipated by some researchers[8,9].

More recently, a new generation of non-contrast flow assessment in ultrasound technology, considered the third generation, has emerged[4,10]. These include non-invasive flow modalities that are expected to overcome the pitfalls of CDI and PDI, discussed later in this article, thereby enhancing the visualization of microscopic blood vessels in tissues and lesions[4,10]. These techniques allow users to examine the main blood vessels and the microvasculature within smaller organs and all sorts of lesions (superficial and deep) better[10]. Ultrasound practitioners must be familiar with these new flow imaging technological tools, which can be implemented by pushing a button on the ultrasound equipment.

This article presents recent updates on the various non-contrast ultrasound flow modalities available in daily ultrasound practice. The process involved reviewing the current literature and providing information based on the authors' decades of clinical ultrasound expertise. This review article can be a 'one-stop-shop' for information on non-contrast flow ultrasound modalities.

Doppler principle in ultrasound

The "Doppler effect" was discovered in 1842 by an Austrian physicist, Christian Doppler[11]. This discovery, and many other ultrasound-related discoveries, like that of Ian Donald in 1958[12,13], led to a complete revolutionization of medical diagnosis and patient pathways. The Doppler effect in ultrasound provides real-time, non-invasive, and non-ionizing insights into blood flow dynamics within the heart and blood vessels[3], rendering it an essential instrument for diagnostic accuracy in modern ultrasonography, thereby aiding clinical decision-making.

While brightness mode (B-mode) imaging employs the amplitude of reflected echoes to construct a 2D image, Doppler ultrasonography assesses the frequency of the returning echo to ascertain relative motion[14]. Doppler ultrasound relies on the Doppler effect to assess blood flow movement within the body[15]. The technique is founded on a simple yet profound principle which states that *"when a sonic source is moving towards or away from a stationary listening device, the relative frequency heard by the device will be shifted according to the velocity of the source"*[16]. In order to visualize blood vessels using Doppler imaging, the transducer generally serves as the fixed element. Meanwhile, the dynamic reflectors generating the returning signal echoes are represented by the movement of red blood cells[3].

Blood moving towards the transducer increases in ultrasound frequency (positive frequency shift), whereas blood moving away from the transducer decreases ultrasound frequency (negative frequency shift). This is shown in Fig. 1.

The frequency shift[15] can be calculated from the equation below:

$$\Delta Fs = 2V foCos\theta / C$$

$$\text{Frequency shift} = \frac{2 \times \text{blood flow velocity} \times \text{transmission frequency} \times \cos(\text{insonation angle})}{\text{Speed of sound in the tissue}}$$

The traditional Doppler principle has been employed in many ultrasound modalities including color Doppler, power Doppler, and spectral Doppler (pulsed wave Doppler, continuous wave Doppler).

Spectral Doppler

Spectral Doppler can be explained as a graphic representation of blood flow, direction, and velocity. It is obtained from the blood vessel lumen when pulse wave Doppler (PWD) or continuous wave Doppler (CWD) has been applied; therefore, graphic and waveform representation of PWD and CWD is known as spectral display or spectral Doppler. It depends on the location or area within the blood vessel lumen and the amount of red blood cells within the interrogated region of interest. It can also be described as a quantitative visual presentation of blood flow information, and it is a real-

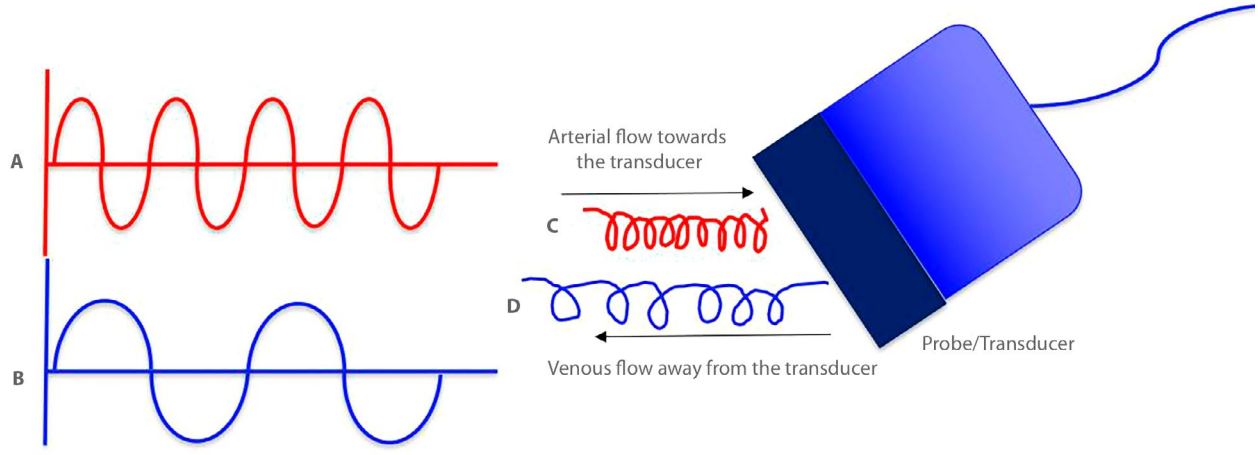

Fig. 1. *Waveforms of arterial blood* **(A)** *flow towards the transducer, and venous blood* **(B)** *flow away from the transducer. The waveforms illustrate a higher frequency (4 cycles per second) of the arterial flow (a positive shift) than the venous flow frequency (2 cycles per second) within the same period. This is further illustrated* **(C, D)** *using metal spring diagrams where there are more compressions on the spring pattern representing flow towards the transducer and more regions of rarefactions on the spring pattern representing flow away from the transducer*

time presentation of Doppler shift versus time on the vertical and horizontal display axes. Spectral display provides flow information (presence, direction, speed, and character) at the interrogation site[17]. Peak systolic and end-diastolic velocities are derived from spectral waveform, reflecting spectral Doppler (Fig. 2).

Spectral Doppler velocimetry involves systematic analysis of the spectrum of frequencies that constitute the Doppler signal[18]. CWD consists of a double-element transducer that transmits and receives ultrasound signals; one continuously emits ultrasound, and the other constantly receives backscattered echoes. It can calculate very high velocities. PWD ultrasound consists of a single transducer crystal that emits a pulse of short bursts of ultrasound energy; the same crystal also serves as the receiver transducer, i.e., one crystal acts as both the transmitter and receiver of ultrasound signal[3]. PWD measures flow velocities in vessels at a target and exact location; however, this evaluation method makes PWD vulnerable to aliasing at higher velocities, especially at target structures further away from the transducer. CWD allows the detection of very high peak flow velocities without the ability to pinpoint the location of the actual flow (as in cardiac evaluations)[3].

Color Doppler imaging (CDI)

Principle and physics

CDI integrates data on the velocity of moving objects onto a standard B-mode image. It relies on the Doppler effect and the frequency (or wavelength) change of sound waves when they encounter moving red blood cells[19]. To achieve this, a Doppler box is positioned over a region of interest. By analyzing the frequency and amplitude of echoes generated from the interrogation of that region using multiple pulse sequences, the machine provides information about the flow in that specific area. Colors are then assigned based on the direction of flow, known as phase shift, with red typically indicating flow towards the transducer and blue indicating flow away from the transducer[20]. However, these fixed color codings (red and blue) were introduced at inception, and nowadays can be used interchangeably during real-time scanning.

Furthermore, the machine calculates a color shade determined by the mean frequency shift of an interrogated pixel, representing the mean velocity of flow in that region. Lighter shades are typically associated with faster-moving objects, while darker shades indicate slower-moving objects[16]. It provides real-time information about blood flow direction and velocity.

Applications

Used for quick assessment of blood flow (including turbulent flow, for example, in a region of stenosis) in large vessels and organs, and to identify areas of interest for further Doppler examination.

CDI is pivotal in diagnosing vascular conditions such as deep vein thrombosis (DVT), carotid artery disease, and peripheral artery disease (PAD). In obstetrics, CDI monitors fetal well-being by assessing umbilical blood flow. Users of ultrasound in cardiology departments utilize CDI to evaluate heart valve function and detect abnormalities in blood flow within the heart. CDI is also invaluable during interventional procedures, providing guidance for the placement of intravenous catheters and/or measuring blood flow before and after procedures like angioplasty or stent placement.

Despite its advantages in ultrasound assessment, CDI is limited to qualitative assessment of flow velocities without providing quantitative or measurable values. Furthermore, CDI has limitations in assessing slow flow in smaller vessels accurately.

Power Doppler imaging (PDI)

PDI evaluates the total number of Doppler shifts of the moving cells regardless of direction and speed. This Doppler mode is sensitive to small and weak flow, and is independent of its direction; it is a type of color flow imaging that can display blood flow in small vessels and some slow-flow tissues[21]. It measures the total amplitude of Doppler frequency shift and is independent of velocity, flow direction and insonation angle. The functionality of this flow imaging is based on the intensity of the blood flow rather than the direction of flow, therefore aliasing does not affect PDI.

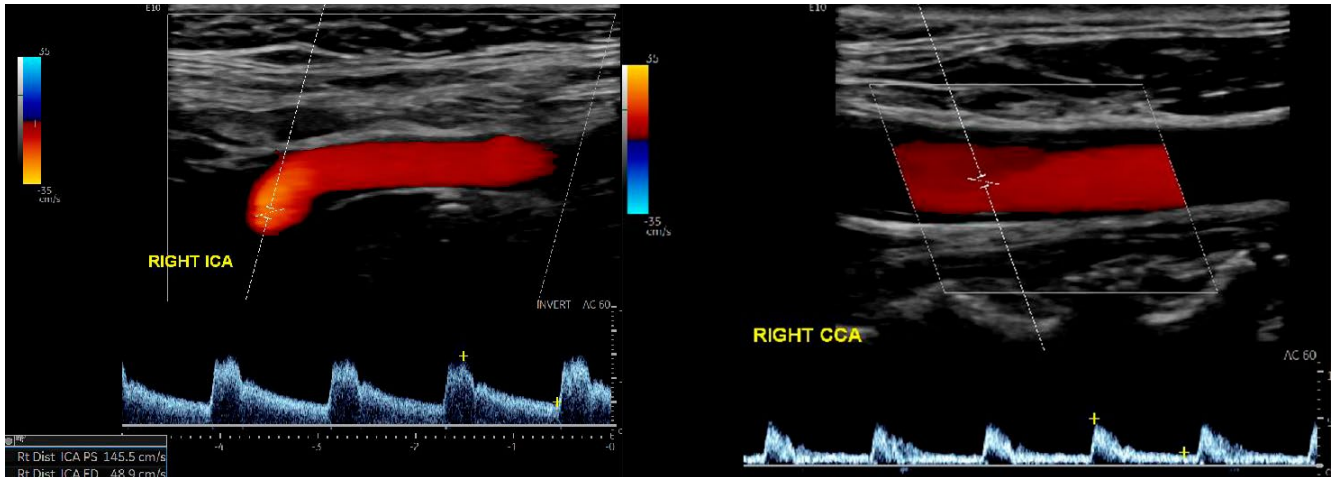

Fig. 2. *Sonograms of the right internal (ICA) and common carotid arteries (CCA) showing spectral Doppler waveforms and measurements of the PSV and EDV within the lumen of the vessels – images by E.A.*

PDI allows the detection of lower velocities and higher flow sensitivity than color flow, which is why it may be favored over CDI because of its sensitivity to small flow in capillaries and small vessels[22,23]. PDI is a Doppler method in which the power or intensity of the Doppler signal is measured and mapped in color rather than the Doppler frequency shift[24].

Limitations of PDI include a slower frame rate compared to color Doppler, which renders this imaging method less valuable for examining rapidly moving vessels, non-cooperative patients (especially children), and areas subject to respiratory or cardiac motion, such as subphrenic hepatic lesions. Also, PDI does not provide flow direction information[24]. PDI is also useful when examining superficial structures like the thyroid, testes, renal grafts, subcutaneous lesions, and deep organs like the liver, uterus, endometrium, and ovaries[25].

Advanced dynamic flow (ADF)

ADF is a third-generation non-contrast Doppler flow technology released in the early 2000s by Toshiba Medical Systems that was reported to provide high detection of microvascularities and is considered to be an improvement on PDI[26]. Unlike PDI, ADF shows information about flow directionality and calculates velocity. So far, due to its reduced blooming, ADF has gained popularity in obstetric ultrasound, commonly used to evaluate fetal umbilical vessels and heart chambers[27]. Despite the increased use of ADF in clinical obstetric ultrasound, some studies have found ADF to be less sensitive than CDI, PDI, and McVI in detecting small and slow-flowing blood vessels in other anatomical areas, as presented in the related literature section of this article.

Microvascular imaging (McVI)

Due to the limitations of CDI and PDI in their ability to separate clutter artefacts from microvascular flow signals, a new ultrasound flow technology, called Superb Microvascular Imaging (SMI), was developed and introduced in 2013 by Toshiba Medical Systems, now Canon Medical Systems (Otawara, Tochigi, Japan)[9,28]. After this, further ultrasound equipment manufacturers have provided users with their versions of this technology (Tab. 1), which are collectively classed as McVI in this article.

McVI is a technology that can separate motion artefacts from microscopic vascularity through the application of a special wall filter which, unlike the traditional Doppler techniques, does not filter out the low and flash artefacts[9,28]. This filter can utilize a unique Doppler algorithm to suppress/separate the artefact from the blood flow signals (Fig. 3), thus significantly improving the ultrasound visualization of microvasculature (Fig. 4 and Fig. 5)[29]. Advantages of McVI is that it allows visualization of blood vessels less than 1 mm in diameter at a velocity of less than 0.2 cm/s[9]. This is done at high frame rates of up to 50 frames per second (50 fps), with little or no noise artefacts from motion within the tissue or organ due to respiration, vascular pulsation, or subtle movements by patients[30].

McVI is generally available in color and monochromatic modes[26]. The former provides microvascular information as an overlay on the background B-mode (grayscale) ultrasound images. Color McVI is similar in appearance to the traditional CDI and PDI flow display and helps ultrasound practitioners visualize the anatomical orientation of the organ or lesion being examined[31]. Monochromatic McVI provides detailed and focused information on the microvasculature alone, while subtracting the background B-mode, which has been reported to be more sensitive than color McVI in detecting microvascularity[29]. Currently, the monochromatic mode of McVI is unavailable on all ultrasound equipment brands.

Introducing the Vascularity Index (VI) feature gives ultrasound practitioners the unique opportunity to objectively calculate the amount of blood flow within a designated area of the screen image[32]. This is achieved by the ultrasound machine using a special algorithm that calculates the ratio of the color pixels to the entire pixel on the ultrasound screen[32]. The function serves as a unique diagnostic tool for ultrasound practitioners and clinical researchers, as presented in the literature review section of this article.

It is worth mentioning that a high computational complexity is required to support McVI, creating the need for an advanced ultrasound probe design with a newer matrix[33]. This improved third-

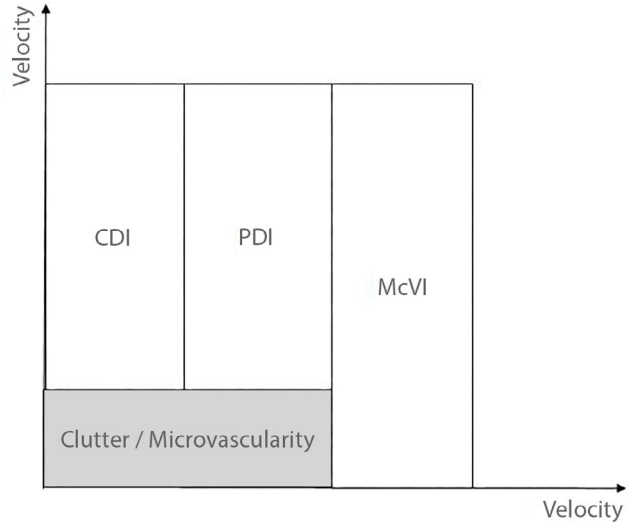

Fig. 3. *A simple chart showing the various Doppler modalities with their corresponding velocity ranges. CDI and PDI have filtered out clutter artefacts within similar velocities as microvascular velocity flow signals. McVI can separate the clutter from microvascular flows*

Tab. 1. Summary of various non-contrast ultrasound flow modes. Microvascular imaging (McVI) nomenclatures used by different ultrasound manufacturers (listed alphabetically)

Company	Canon Medical Systems	General Electric Healthcare	Hitachi Medical Systems	Philips Healthcare	Samsung Medison	Siemens Healthineers
Brand name	Superb Microvascular Imaging	MicroVascular Imaging	eFlow	MicroFlow Imaging	MicroVascular Flow	Slow Flow
Acronym	SMI	MVI	–	MFI	MV Flow	-

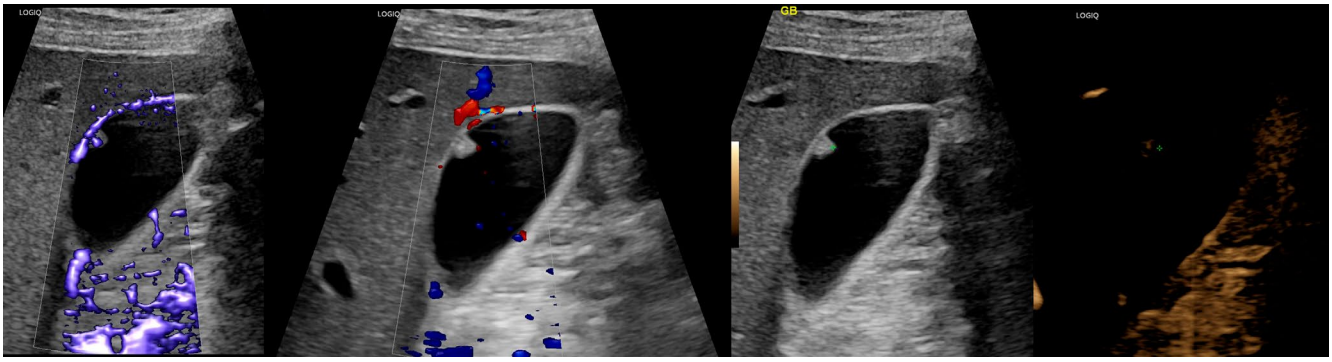

Fig. 4. *A 7 mm polyp in the gallbladder of a 42-year-old male. Color Doppler with a low PRF setting revealed no vascularity evidence. Microvascular imaging revealed a feeder vessel from the gallbladder wall into the polyp. Dual-display B-mode-B-flow ultrasound also revealed subtle evidence of the feeder vessel (adjacent to the caliper) – images by E.B.*

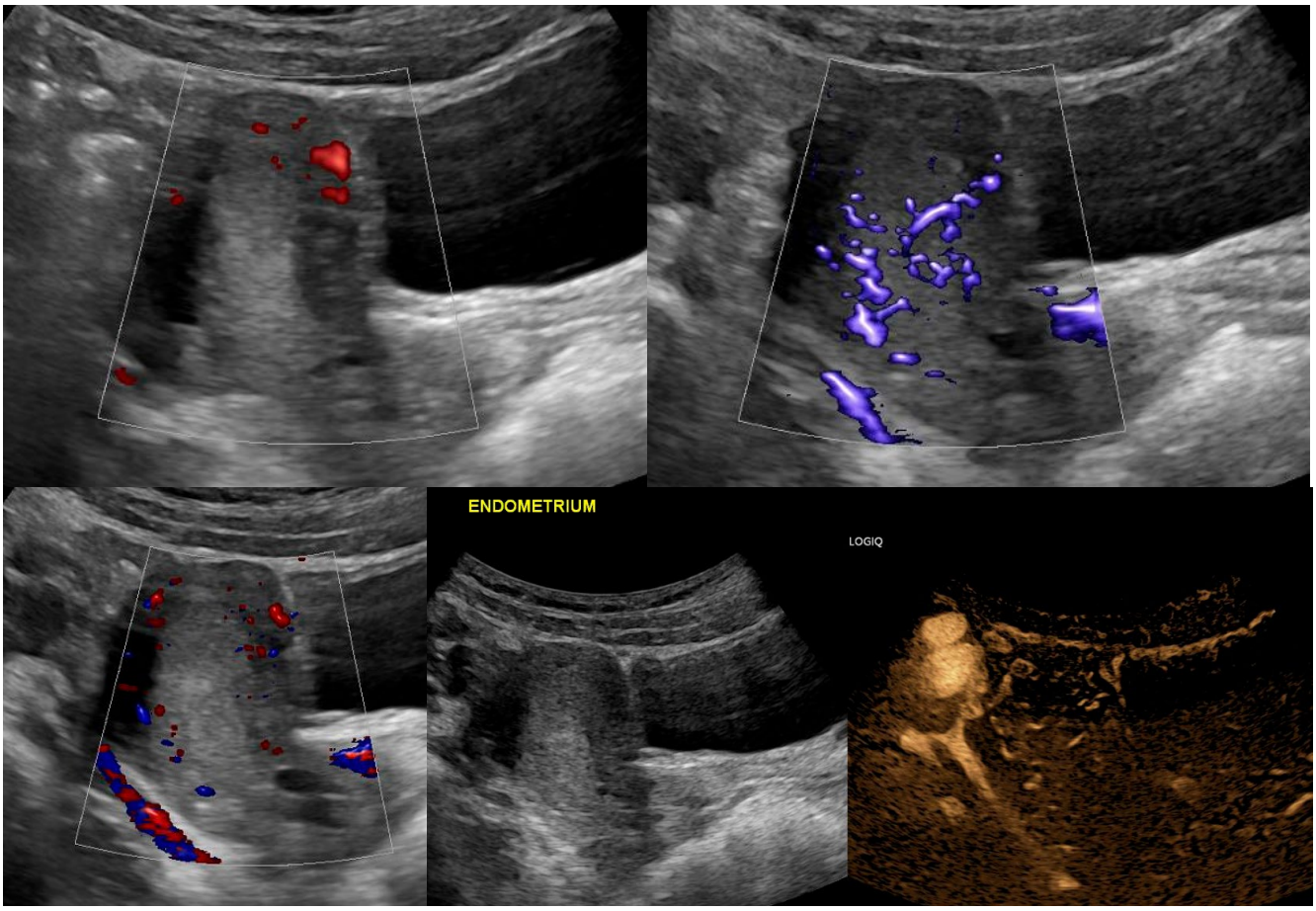

Fig. 5. *Abnormally thickened endometrium (18.6 mm anteroposteriorly) in a 12-year-old female with symptoms of abnormal uterine bleeding. PDI and CDI showed some myometrial vessels with no significant flow evidence in the endometrium. B-flow showed the myometrial vessels with tiny vessels within the endometrium. McVI revealed evidence of endometrial hypervascularity that was not evident on CDI/PDI – images by E.B.*

generation Doppler flow function is only available in the more contemporary, top-end (and more recently, some mid-range), full-unit ultrasound machine models. Thus, it excludes most table-tops and hand-held ultrasound devices for emergency and community-based practice, limiting availability to affordability. McVI has other technical limitations as well. Unlike its traditional Doppler counterparts, the sensitivity of McVI is negatively affected by the depth of the organ being examined[33]. In addition, similar to PDI but unlike CDI, McVI does not provide directional information on blood flow, as the technology focuses on flow intensity[34]. McVI has a smaller Doppler box limited to a specific size, unlike PDI and CDI, which can be adjusted to fit the entire scan window[28]. Furthermore, although McVI provides improved information on minute blood vessels, it does not supply information on the 'wash-in' and 'washout' principles used in CEUS[34]. This principle is a critical phenomenon CEUS uses to categorize some lesions into benign/malignant groups without the requirement for CT/MRI characterization[9]. Based on clinical experience, McVI is unavailable on all

the probes of some third-generation Doppler-equipped ultrasound machines (Tab. 2).

Doppler clinical adjustments

To improve the sensitivity of Doppler assessment in clinical practice, there are several settings that can be optimized. Techniques for improving ultrasound machine settings and thus Doppler assessments include: 1) reduction of the size of the Doppler box; 2) optimization of the color gain; 3) optimization of the pulse repetition frequency (PRF); 4) reduce the wall filter. All of these as such will improve the overall frame rate[3,32,35]. However, applying these techniques tends to increase the background noise due to increased detection of Doppler signals from motion (or flash/clutter) artefacts[9]. These artefacts slip through the mono-dimensional color Doppler wall filter and are within similar velocity bandwidths as microvasculature (Fig. 2)[9,28]. Therefore, ultrasound practitioners are forced to compromise between detecting clutter artefacts and the absence of microvascularity in practice or consider other imaging modalities that are not without limitations.

Related literature

Since its introduction in clinical practice, scholars have published many research works using McVI in various organs, comparing its performance to the other Doppler flow techniques (CDI, PDI, ADF) and CEUS. We present our review of some related literature on this topic.

In vascular applications, Curti *et al.*[36] studied 122 patients who had an endovascular abdominal aortic aneurysm repair (EVAR) procedure. The researchers studied the usefulness of McVI against CEUS in detecting and classifying type II endoleak in the follow-up of post-EVAR patients. This was compared with the findings on CTA as a reference. Their study found McVI and CEUS to have the same sensitivity of 91.5% and specificity of 100% respectively, with a high percentage of agreement between McVI/CEUS and CTA at 94.9%.

In abdominal applications, Mao *et al.*[37] conducted a study on 144 solid renal masses examined using CDI, McVI, and CEUS to compare and grade the internal microvasculature. In their study, CDI's blood flow detection rate was 78.5%, McVI 88.9%, and CEUS 93.8%. This led the authors to conclude that McVI is comparable to CEUS and valuable in classifying renal masses, and can provide helpful information on vascular structure and diameter. This was in agreement with another study by Mu *et al.*[29] that also found McVI to be sensitive in differentiating renal lesions into their appropriate Bosniak categories. However, unlike CEUS, McVI performed worse in examining deep-sitting lesions. In contrast, McVI demonstrated usefulness in scanning renal allografts due to its more superficial location. McVI can play a role in predicting chronic allograft damage, according to a recent study by Gürbüz *et al.*[38] on 68 renal allografts where McVI detected the most laterally-located vessel within the graft.

Beyond renal applications, a study by Ozlem *et al.*[39] on 43 patients with chronic hepatitis determined the sensitivity of McVI, ADF, CDI and PDI in predicting liver fibrosis compared to the results from liver biopsy. The researchers used vascular architecture with appearances such as vascular blunting and tortuosity to predict the severity of fibrosis. In their study, McVI helped distinguish the vascular hepatic changes, accurately predicting cirrhosis and fibrosis in their patients.

Still within hepatic applications, Lee *et al.*[40] utilized McVI in characterizing 29 hepatic lesions by their unique vascular architecture. The researchers found McVI to be a useful non-contrast ultrasound

Tab. 2. Summary of various non-contrast ultrasound flow modes

Flow mode	CDI	PDI	ADF	McVI	B-flow
Working principle	Doppler	Doppler	Doppler	Doppler	Non-Doppler
Generation	1st Gen.	2nd Gen.	3rd Gen.	3rd Gen.	3rd Gen.
Major pros	1. Adjustable Doppler box 2. Provides flow directionality information 3. Available on all ultrasound machines and probes 4. Better penetration than MVI and B-flow	1. More sensitive than CDI 2. Adjustable Doppler box 3. Available on all ultrasound machines and probes 4. Better penetration than MVI and B-flow	1. Suitable for examining the fetal placental vessels and fetal heart chambers 2. Shows flow directionality	1. The most sensitive (non-contrast) flow mode to microvascularity 2. Can prevent the need for other invasive or radiation examinations	1. Not angle-dependent 2. Sensitive to slow flows 3. Can visualize tiny vessels 4. Provides flow information of the entire ultrasound screen; no Doppler box is required
Major cons	1. Filters out microvascularity 2. Angle dependent 3. Prone to aliasing	1. Filters out microvascularity 2. Focuses more on flow intensity over velocity	1. Least sensitive to microvascularity 2. Provided by only one manufacturer	1. Doppler box is limited in size. 2. Only available on high-end ultrasound machines 3. Not available on all ultrasound probes 4. Less sensitive than CDI and PDI in deeper organs 5. Focuses more on flow intensity over velocity	1. No information on flow directionality 2. Provided by only one manufacturer 3. It is not currently available on all ultrasound probes 4. Less sensitive than CDI and PDI in deeper organs 5. Focuses more on flow intensity over velocity

technique in visualizing the vascular patterns of hepatic tumors which improved the diagnosis of hepatic tumors ultrasonically.

Ayaz *et al.*[26] researched the detection of microvascularity in 146 pediatric ovaries using McVI, CDI, PDI, and ADF, while another study[34] focused on neonatal testicles. Both studies found SMI to be the most sensitive flow tool, followed by PDI, CDI, and ADF being the least sensitive (p <0.001).

Cai *et al.*[41] retrospectively assessed the ultrasound images of 238 breast lesions to evaluate the Vascularity Index (VI) and Vascular Architecture (VA) of each lesion using 3D-McVI. They found that combining B-mode ultrasound with McVI improved diagnostic accuracy in classifying breast lesions to their accurate BI-RADS category.

In a study conducted by Sim, Lee, and Hong[42] on 147 abnormal cervical lymph nodes, McVI (86.9%) had a significantly higher sensitivity than PDI (54.1%) (p <0.001) in categorizing the lymph nodes. However, their study had an under-represented sample of individuals older than forty.

Rumolo *et al.*[43] reported a case of how the application of McVI, along with CDI and PDI, helped improve the diagnosis of hidradenitis suppurativa, a chronic skin disease condition, presenting as a painful left inguinal node.

Alis *et al.*[44] conducted a study that compared the performance of McVI with PDI in detecting blood flow within the inflamed synovium of patients with clinically diagnosed juvenile arthritis using the vascularity index (VI). They found that McVI caught more blood flow evidence of inflammation in some regions than PDI could.

Lastly, Aghabaglou *et al.*[33] compared the sensitivity of McVI to MFI, CDI, and PDI in the fingertip. They found McVI to be comparable to MFI, with higher sensitivities than CDI and PDI. This was the only study encountered that compared microvascular imaging modalities between different manufacturers.

This review article differs from the published literature in that it focuses on the principle and design of the individual flow modalities, their strengths, limitations, and applications in clinical practice.

B-flow imaging

B-flow imaging, introduced in 2000 by GE Healthcare (Chicago, IL, USA), was initially used for vascular assessment, as it was only available on high-frequency linear transducers used for those kinds of studies[45]. Its application has widened over the years, extending to the curvilinear transducers used for more general ultrasound imaging. 'Blood flow B-mode imaging' or 'B-flow' is a non-Doppler ultrasound function designed to evaluate blood flow within the examined body area[46,47]. Using digital encoding software and blood tissue equalization, B-flow overcomes some significant pitfalls of Doppler ultrasound, like angle dependency and the limited detection of slow flow[47]. B-flow acquires images using the same technology as the conventional B-mode ultrasound[47]. However, it suppresses the signal from the still surrounding tissue while enhancing the signals from the flowing red cells within the blood vessels, which would have been initially masked by insufficient Dynamic Range on B-mode (Fig. 4 and Fig. 5)[48]. Furthermore, color Doppler technology overlays the flow information on the pre-existing B-mode display; this uses high computational power, reducing the frame rate and potentially impairing image quality[49]. Since B-flow uses B-mode technology, it provides a better frame rate than CDI and PDI during flow ultrasound, and does not require a Doppler box (Tab. 2)[50].

Since the introduction of B-flow, it has been well-utilized for vascular imaging and hemodynamic studies across diverse specialties. Some studies compared B-flow to Doppler in evaluating arterial plaques in the femoral and carotid arteries, where it was reported to provide a correct diameter of the vessels due to its lack of 'color flash artefact' from tissue movement and 'color blooming' over the vessel wall seen on Doppler[51–53]. While one study[54] reported the application of B-flow in evaluating microembolism in the cerebral artery, other studies have looked at the application of B-flow in evaluating vascularity within the native (Fig. 5) and transplant liver and kidney[55]. A recent scoping review by Hofmann *et al.* compiled evidence on the applications of B-flow in the hepatic parenchymal and lesion vasculature, the assessment of native and transplant kidneys, obstetrics, vascular, and hysterosalpingo-contrast sonography (HyCoSy) assessment of the uterine tubes[56]. While B-flow appeared well-praised in these areas, the authors could combine some of their evidence from the limited case reports and older research literature available.

Significant limitations of B-flow include its limited sensitivity in evaluating flow in deep anatomical structures and the lack of flow directionality, unlike in Doppler, where the flow is color-coded as blue or red primarily, which traditionally represents flow away from or towards the transducer, respectively[48]. B-flow is only available on one ultrasound manufacturer's platform. It is also unavailable on some ultrasound probes and not on the tabletops and handheld portable ultrasound equipment provided by the same manufacturer.

Conclusion

Doppler ultrasound is an essential imaging tool for diagnosing and assessing many disease processes. The newer and improved Doppler (and non-Doppler) techniques have recently resulted in further advancements in the uses of Doppler to evolve the role of ultrasound assessment in areas that were previously considered impossible to visualize. Ultrasound users are encouraged to explore the underlying principles to appreciate the advantages and pitfalls of each technique.

Conflict of interest

The authors do not report any financial or personal connections with other persons or organizations which might negatively affect the contents of this publication and/or claim authorship rights to this publication.

Author contributions

Original concept of study: EAB. Writing of manuscript: EAB, CA, EA, RR. Final acceptation of manuscript: EAB, CA, EA, RR. Collection, recording and/or compilation of data: EAB, Critical review of manuscript: EAB, RR.

References

1. Newman PG, Rozycki GS: The history of ultrasound. Surg Clin North Am 1998; 78: 179–195. doi: 10.1016/s0039-6109(05)70308-x.
2. Lugano R, Ramachandran M, Dimberg A: Tumor angiogenesis: causes, consequences, challenges and opportunities. Cell Mol Life Sci 2020; 77: 1745–1770. doi: 10.1007/s00018-019-03351-7.
3. Löwe A, Jenssen C, Hüske S, Zander D, Ignee A, Lim A *et al.*: „Knobology "in Doppler Ultrasound. Med Ultrason 2021; 23: 480–486. doi: 10.11152/mu-3216.
4. Bartolotta TV, Taibbi A, Randazzo A, Gagliardo C: New frontiers in liver ultrasound: From mono to multi parametricity. World J Gastrointest Oncol 2021; 13: 1302–1316. doi: 10.4251/wjgo.v13.i10.1302.
5. Golemati S, Cokkinos DD: Recent advances in vascular ultrasound imaging technology and their clinical implications. Ultrasonics 2022; 119: 106599. doi: 10.1016/j.ultras.2021.106599.
6. Ignee A, Atkinson NS, Schuessler G, Dietrich CF: Ultrasound contrast agents. Endosc Ultrasound 2016; 5: 355–362. doi: 10.4103/2303-9027.193594.
7. Beckmann S, Simanowski JH: Update in contrast-enhanced ultrasound. Visceral Medicine 2020; 36: 476–486. doi: 10.1159/000511352.
8. Santolamazza G, Virdis F, Abu-Zidan F, Cioffi SPB, Reitano E, Altomare M *et al.*; PseAn Collaborative Group; Cimbanassi S: Contrast-enhanced ultrasound (CEUS) in the follow-up of abdominal solid organ trauma: an international survey prior to the PseAn study. Eur J Trauma Emerg Surg 2023 Oct 13. doi: 10.1007/s00068-023-02364-z. Erratum in: Eur J Trauma Emerg Surg. 2024 Mar 27. doi: 10.1007/s00068-024-02491-1.
9. Wilson A, Lim AKP. Microvascular imaging: new Doppler technology for assessing focal liver lesions. Is it useful? Clin Radiol 2022; 77: e807–e820. doi: 10.1016/j.crad.2022.05.032.
10. Yoo J, Je BK, Choo JY: Ultrasonographic demonstration of the tissue microvasculature in children: microvascular ultrasonography versus conventional color Doppler ultrasonography. Korean J Radiol 2020; 21: 146–158. doi: 10.3348/kjr.2019.0500. Erratum in: Korean J Radiol 2020; 21: 509. doi: 10.3348/kjr.2020.0208.
11. Katsi V, Felekos I, Kallikazaros I: Christian Andreas Doppler: A legendary man inspired by the dazzling light of the stars. Hippokratia 2013;17: 113–114.
12. Donald I. Investigation of abdominal masses by pulsed ultrasound. Classic Papers in Modern Diagnostic Radiology. 2004 Nov 23: 213.
13. Nowicki A, Reid JM: An infinite gate pulse Doppler. Ultrasound in Medicine & Biology 1981; 7: 41–50. doi: 10.1016/0301-5629(81)90021-1.
14. Brandestini MA, Eyer MK, Stevenson JG: M/Q-Mode Echocardiography. In: Lancée CT (ed): Echocardiology. Developments in Cardiovascular Medicine. 1979 Springer, Dordrecht, pp. 441–446. doi: 10.1007/978-94-009-9324-2_61.
15. Omoto R, Chihiro Kasai C: Basic principles of Doppler color flow imaging. Echocardiography 1986; 3: 463–473.
16. Shah A, Irshad A: Sonography Doppler Flow Imaging Instrumentation. InStatPearls [Internet] 2023 May 1. StatPearls Publishing.
17. Kremkau FW: Principles of spectral Doppler. Journal for Vascular Ultrasound. 2011; 35: 214–228. doi: 10.1177/154431671103500405.
18. Maulik D: Spectral Doppler: basic principles and instrumentation. In: Maulik D (ed.): Doppler ultrasound in obstetrics and gynecology. Cham, Springer International Publishing 2023: pp. 19–34.
19. Harris P, Kuppurao L: Quantitative Doppler echocardiography. BJA Education 2016; 16: 46–52. https://doi.org/10.1093/bjaceaccp/mkv015.
20. Evans DH, Jensen JA, Nielsen MB: Ultrasonic colour Doppler imaging. Interface Focus 2011; 1: 490–502. doi: 10.1098/rsfs.2011.0017.
21. Smith E, Azzopardi C, Thaker S, Botchu R, Gupta H: Power Doppler in musculoskeletal ultrasound: uses, pitfalls and principles to overcome its shortcomings. J Ultrasound 2021; 24: 151–156. doi: 10.1007/s40477-020-00489-0.
22. Cutolo M, Smith V: Detection of microvascular changes in systemic sclerosis and other rheumatic diseases. Nat Rev Rheumatol 2021; 17: 665–677. doi: 10.1038/s41584-021-00685-0.
23. Martinoli C, Derchi LE, Rizzatto G, Solbiati L: Power Doppler sonography: general principles, clinical applications, and future prospects. Eur Radiol 1998; 8: 1224–1235. doi: 10.1007/s003300050540.
24. Pellerito J, Polak JF: Introduction to Vascular Ultrasonography E-Book. 7th Edition, Elsevier Health Sciences, 2019.
25. Aziz MU, Eisenbrey JR, Deganello A, Zahid M, Sharbidre K, Sidhu P, Robbin ML: Microvascular flow imaging: A state-of-the-art review of clinical use and promise. Radiology 2022; 305: 250–264. doi: 10.1148/radiol.213303
26. Ayaz E, Aslan A, Inan I, Yıkılmaz A: Evaluation of ovarian vascularity in children by using the "superb microvascular imaging" ultrasound technique in comparison with conventional Doppler ultrasound techniques. J Ultrasound Med 2019; 38: 2751–2760. doi: 10.1002/jum.14983.
27. Hidaka N, Chiba Y: Three-dimensional ultrasonic angiography of fetal, umbilical and placental vasculature using advanced dynamic flow. J Med Ultrasound 2005; 13: 74–78.
28. Cannella R, Pilato G, Mazzola M, Bartolotta TV: New microvascular ultrasound techniques: abdominal applications. Radiol Med 2023; 128: 1023–1034. doi: 10.1007/s11547-023-01679-6.
29. Mu J, Mao Y, Li F, Xin X, Zhang S: Superb microvascular imaging is a rational choice for accurate Bosniak classification of renal cystic masses. Br J Radiol 2019; 92: 20181038. doi: 10.1259/bjr.20181038.
30. Hata J: Seeing the unseen: new techniques in vascular imaging Superb Microvascular Imaging. In: Toshiba Medical Review, Tokyo, Toshiba Leading Innovation 2014; 13: 1–8.
31. Ayaz E, Ayaz M, Önal C, Yıkılmaz A: Seeing the unseen: evaluating testicular vascularity in neonates by using the superb microvascular imaging ultrasound technique. J Ultrasound Med 2019; 38: 1847–1854. doi: 10.1002/jum.14882.
32. Fu Z, Zhang J, Lu Y, Wang S, Mo X, He Y, Wang C, Chen H: Clinical applications of superb microvascular imaging in the superficial tissues and organs: a systematic review. Acad Radiol 2021; 28: 694–703. doi: 10.1016/j.acra.2020.03.032.
33. Aghabaglou F, Ainechi A, Abramson H, Curry E, Kaovasia TP, Kamal S *et al.*: Ultrasound monitoring of microcirculation: An original study from the laboratory bench to the clinic. Microcirculation 2022; 29: e12770. doi: 10.1111/micc.12770.
34. Aziz MU, Eisenbrey JR, Deganello A, Zahid M, Sharbidre K, Sidhu P, Robbin ML: Microvascular flow imaging: A state-of-the-art review of clinical use and promise. Radiology 2022; 305: 250–264. doi: 10.1148/radiol.213303.
35. Corvino A, Varelli C, Cocco G, Corvino F, Catalano O: Seeing the unseen with superb microvascular imaging: Ultrasound depiction of normal dermis vessels. J Clin Ultrasound 2022; 50: 121–127. doi: 10.1002/jcu.23068.
36. Curti M, Piacentino F, Fontana F, Ossola C, Coppola A, Marra P *et al.*: EVAR follow-up with ultrasound superb microvascular imaging (SMI) Compared to CEUS and CT angiography for detection of Type II Endoleak. Diagnostics (Basel) 2022; 12: 526. doi: 10.3390/diagnostics12020526.
37. Mao Y, Mu J, Zhao J, Yang F, Zhao L: The comparative study of color doppler flow imaging, superb microvascular imaging, contrast-enhanced ultrasound micro flow imaging in blood flow analysis of solid renal mass. Cancer Imaging 2022; 22: 21. doi: 10.1186/s40644-022-00458-2.
38. Gürbüz AF, Keven A, Elmalı A, Toru S, Apaydın A, Çeken K: A comparison between the superb microvascular imaging technique and conventional Doppler ultrasound in evaluating chronic allograft damage in renal transplant recipients. Diagn Interv Radiol 2023; 29(2):212–218. doi: 10.5152/dir.2022.21555.
39. Balık AÖ, Kılıçoğlu ZG, Görmez A, Özkara S: Radiology-pathology correlation in staging of liver fibrosis using superb microvascular imaging. Diagn Interv Radiol 2019; 25: 331–337. doi: 10.5152/dir.2019.18231.
40. Lee DH, Lee JY, Han JK: Superb microvascular imaging technology for ultrasound examinations: Initial experiences for hepatic tumors. Eur J Radiol 2016; 85: 2090–2095. doi: 10.1016/j.ejrad.2016.09.026.
41. Cai S, Wang H, Zhang X, Zhang L, Zhu Q, Sun Q, Li J, Jiang Y: Superb microvascular imaging technology can improve the diagnostic efficiency of the BI-RADS system. Front Oncol 2021; 11: 634752. doi: 10.3389/fonc.2021.634752.
42. Sim JK, Lee JY, Hong HS: Differentiation between malignant and benign lymph nodes: role of superb microvascular imaging in the evaluation of cervical lymph nodes. J Ultrasound Med 2019; 38: 3025–3036. doi: 10.1002/jum.15010.
43. Rumolo M, Santarsiere M, Menna BF, Minelli R, Vergara E, Brunetti A, Gisonni P: Color doppler and microvascular flow imaging to evaluate the degree of inflammation in a case of hidradenitis suppurativa. Journal for Vascular Ultrasound 2022; 46: 67–70. 10.1177/15443167211066491.
44. Alis D, Erol BC, Akbas S, Barut K, Kasapcopur O, Adaletli I: Superb microvascular imaging compared with power doppler ultrasound in assessing synovitis of the knee in juvenile idiopathic arthritis: A preliminary study. J Ultrasound Med 2020; 39: 99–106. doi: 10.1002/jum.15079.
45. Weskott HP: B-Flow – eine neue Methode zur Blutflussdetektion [B-flow – a new method for detecting blood flow]. Ultraschall Med 2000; 21: 59–65. German. doi: 10.1055/s-2000-319.
46. Reginelli A, Urraro F, di Grezia G, Napolitano G, Maggialetti N, Cappabianca S *et al.*: Conventional ultrasound integrated with elastosonography and B-flow imaging in the diagnosis of thyroid nodular lesions. 2014; 12: Int J Surg 2014; 12 (Suppl 1): S117–S122. doi: 10.1016/j.ijsu.2014.05.033.

47. Chiao RY, Mo LY, Hall AL, Miller SC, Thomenius KE: B-mode blood flow (B-flow) imaging. Proc. IEEE Int. Symp. Ultrason. Symp. 2000; 2: 1469–1472). doi: 10.1109/ULTSYM.2000.921601.

48. ElShenawy M, Elshazly IM, El Sheikh HE: The Added Value of B-Flow Technique in Assessment of Lower Limb Arterial Lesions with Densely Calcified Atheromatous Plaques. Benha Medical Journal 2021; 38: 280–293.

49. Gümüş T, Yücel C, Oktar S, Özdemir H, Baran ÖN, Ilgit ET: Evaluation of Carotid Artery Plaques with B-Flow Sonography and Comparing the Results with Color, Power Doppler US and DSA. New Trend Med Sci 2021; 2: 50–57.

50. Wang HK, Chou YH, Chiou HJ, Chiou SY, Chang CY. B-flow ultrasonography of peripheral vascular diseases. Journal of Medical Ultrasound 2005; 13: 186–195. doi: 10.1016/S0929-6441(09)60108-9

51. Groth M, Dammann E, Arndt F, Ernst M, Herrmann J: Comparison of B-mode with B-flow sonography for the evaluation of femoral arteries in infants. Rofo. 2017; 189: 1161–1167. English. doi: 10.1055/s-0043-112249.

52. Reiter M, Horvat R, Puchner S, Rinner W, Polterauer P, Lammer J *et al.*: Plaque imaging of the internal carotid artery – Correlation of B-flow imaging with histopathology. Am J Neuroradiol 2007; 28: 122–126.

53. Umemura A, Yamada K: B-mode flow imaging of the carotid artery. Stroke 2001; 32: 2055–2057. doi: 10.1161/hs0901.095648.

54. Si-Mohamed S, Aïchoun I, Schuster I, Di Rienzo M, Dauzat M, Pérez-Martin A, Bouly S: Visualisation du passage de micro-emboles cérébraux par ultrasonographie en mode B-flow [B-mode sonography visualizing microemboli flow in the main cerebral arteries]. J Mal Vasc 2015; 40: 187–191. French. doi: 10.1016/j.jmv.2015.03.002.

55. Dammann E, Groth M, Schild RS, Lemke A, Oh J, Adam G, Herrmann J: B-flow Sonography vs. Color Doppler Sonography for the Assessment of Vascularity in Pediatric Kidney Transplantation. Rofo 2021; 193: 49–60. English. doi: 10.1055/a-1167-8317.

56. Hofmann AG, Mlekusch I, Wickenhauser G, Assadian A, Taher F: Clinical Applications of B-Flow Ultrasound: A Scoping Review of the Literature. Diagnostics (Basel). 2023; 13: 397. doi: 10.3390/diagnostics13030397.