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Superb microvascular imaging (SMI) in the evaluation of musculoskeletal disorders: a systematic review

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Abstract

Objectives To systematically review the current literature concerning the role of superb microvascular imaging (SMI), a novel Doppler technique that enables detection of fine vessels and slow blood flow, in the evaluation of musculoskeletal disorders.

Methods An online search of the literature was conducted for the period 2013 to April 2019 and included original articles written in English language. A data analysis was performed at the end of the literature search.

Results Eight original articles with prospective design and one with retrospective design were included in this review: 4 studies focused on rheumatoid arthritis, 2 on rheumatoid and other arthritides, 1 on lateral epicondylosis and 2 on carpal tunnel syndrome. Sample size ranged from 26 to 83 patients. Despite some methodological differences, all studies compared the performance of SMI with that of a conventional Doppler technique such as power and color Doppler and found an improvement in vascularity detection with SMI. The main variations were in sample size, evaluated parameters and vascularity interpretation methods. Inter-observer agreement for SMI ranged from moderate to excellent.

Conclusions SMI is a promising tool for the diagnosis and treatment planning of different musculoskeletal disorders. Future investigations should include larger samples of patients with long-term follow-up.

Keywords Doppler · Microflow imaging · Musculoskeletal imaging · Superb microvascular imaging · Ultrasound

Introduction

In the recent years, ultrasound (US) has progressively gained a central role in the evaluation of the musculoskeletal system [1–3]. US is a cost-effective, time-saving and noninvasive modality which enables a thorough evaluation of most superficial structures in the musculoskeletal system [4–8] and has the unique capability to visualize the vascularity of soft-tissue structures thanks to the integration with Doppler techniques, such as power Doppler (PD) and color Doppler (CD) imaging [9]. The advent of contrast-enhanced US has improved the detectability of blood microflow [10] without, however, replacing conventional Doppler imaging, as it requires an intravenous administration of contrast agent and is more expensive and unavailable in certain institutions.

Conventional Doppler techniques suffer from technical limitations regarding the visualization of minute blood vessels due to the presence of extraneous Doppler signals arising from clutter, i.e., nearby tissue motion. In fact, wall filters need to be applied to conventional Doppler imaging to remove clutter and motion artifacts. This implies a loss of fine blood vessels visibility, whose flow is slow and almost equals tissue motion velocity [9]. Advanced flow-detection imaging techniques have overcome these limitations. Among them, superb microvascular imaging (SMI; Canon Medical Systems, Otawara, Japan) is a relatively new technique that can differentiate flow signals from overlaying tissue motion artifacts, thus preserving small slow-flow vessels with high detail and definition. SMI analyzes

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clutter motion and adopts a new algorithm to detect and remove tissue motion and reveal actual blood flow, allowing for the assessment of minute vessels with low-velocity blood flow as well [11]. SMI can work in either a monochrome or a color mode. The monochrome mode extracts flow signals from small to large vessels and provides a gray-scale map of flow while subtracting the background information. The color mode depicts the same vessels as a color overlay image, namely giving B-mode and color information simultaneously [11].

The first studies on SMI investigated its role in breast [12–14], testes [15] and thyroid [16]. SMI has recently been proposed as a novel tool for the assessment of different conditions in the musculoskeletal system [17]. Our purpose is to systematically review the current literature concerning the role of SMI in the evaluation of musculoskeletal disorders.

Materials and methods

A systematic review was conducted for the period 2013 to April 2019, starting from the first applications of SMI, using the PubMed and Medline databases. The keywords used were: “superb microvascular imaging”; “superb microvascular imaging”; “microflow imaging”; “microflow ultrasound” and their expansions. The references of identified publications were also checked for further papers to include. Gray literature was also screened for additional publications. Inclusion criteria were: (1) studies dealing with musculoskeletal applications of SMI; (2) involvement of human participants; (3) English language; (4) statement that approval from the local ethics committee and informed consent from each patient or a waiver for it were obtained. Narrative reviews, case reports and case series were excluded from our analysis. From each paper, information regarding demographics, performed examinations, evaluated parameters, SMI assessment and findings was collected. No distinction was made between color and monochrome SMI, as they carry the same information [11]. A data analysis was conducted at the end of the literature search.

Results

The database search process retrieved 134 articles published between 2013 and April 2019; of these, 10 articles dealt with musculoskeletal applications of SMI [18–27]. A case series illustrating the use of SMI for evaluating rheumatoid arthritis [18] and a narrative review dealing with clinical applications of SMI in the skeletal muscle as well as other organs [19] were excluded from our analysis. Reference screening of the selected articles provided one additional paper to include [28]. Thus, 9 papers were finally included in this review [20–28]. These were 8 original prospective and 1 original retrospective articles. A flowchart of the whole process is shown in Fig. 1.

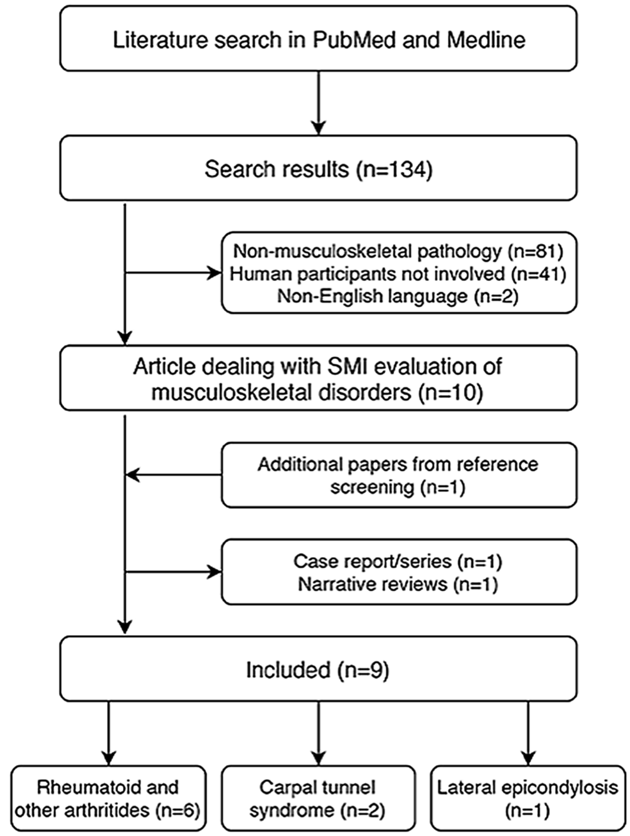

Fig. 1 Flow diagram of study selection. *SMI* superb microvascular imaging

Table 1 shows our data analysis and provides details on the studies evaluating the use of SMI in the assessment of different musculoskeletal disorders. Specifically, four studies focusing on rheumatoid arthritis only, two on rheumatoid and other arthritides, one on lateral epicondylosis and two on carpal tunnel syndrome are included [20–28]. In total, 483 patients and 90 controls were evaluated using SMI. Table 2 shows the scoring systems adopted to interpret vascularity using SMI and conventional Doppler techniques. Figure 2 shows a case of patellar insertional tendinopathy (jumper’s knee) depicted using PD and SMI from our experience.

Meta-analysis of data was not possible due to the low number of papers for each condition and the different parameters evaluated in each study.

Discussion

Our main finding is that clinical application of SMI in the musculoskeletal system has commenced in patients with rheumatoid arthritis, other inflammatory arthritides and osteoarthritis, lateral epicondylosis and carpal tunnel syndrome. Apart from some methodological differences, all

Table 1 Musculoskeletal applications of SMI: analysis of the current literature

Author date	Disease	Sample (n.)	Patient age (y)	Purpose	Instrumental examination/parameters evaluated	Scanned region	Approach/position for SMI assessment	Alignment for SMI assessment	Findings
Li et al. [28]	Rheumatoid arthritis	75 patients 10 controls	57 ± 10	To compare the assessment of joint vascularity by using a semiquantitative scoring system for both PD and SMI	PD score SMI score	MCP joints PIP joints	N/A	N/A	Detection of intra-articular vascularization was improved by SMI ($P < .01$) In comparison with PD, SMI increased 18.5% and 60.0% vascularization in patients with active and inactive disease, respectively With the use of SMI, 43.2% PD signals increased from score 0 to 1 or higher, 25.5% from 1 to 2, 2.8% from 2 to 3 Agreement between DAS28 and PD/SMI: $K = .538$ and .599, respectively No data concerning SMI in controls
Orlandi et al. [25]	Rheumatoid arthritis	30 patients 5 controls	45 (36–64)	To evaluate the use of SMI in patients with early rheumatoid arthritis and those under treatment with rituximab To compare the diagnostic performance of different US modalities in the assessment of synovitis	Synovial thickening (B-mode US) PD score SMI score	Ulnar recess MCP joints PIP joints	Dorsal approach	Axial and longitudinal	Compared with PD, SMI detected vascular signals in more patients with early disease or under treatment with rituximab ($P = .02$) Compared with B-mode US, SMI detected synovial changes in more patients with early disease ($P < .01$) or under treatment with rituximab ($P = .02$) Correlation between DAS28 and PD/SMI: $r = 0.673$ ($P < .01$) and 0.563 ($P < .01$), respectively, with no statistical difference No vascularity on SMI or PD in controls Inter-observer agreement for SMI: $K = .82$
Lim et al. [24]	Rheumatoid arthritis Other inflammatory arthritides and osteoarthritis	19 patients 10 controls 64 patients	44 (29–81)	To assess the efficacy of SMI in detecting low-grade inflammation in joints compared with PD	Presence of PD and SMI signal conspicuity of SMI or PD	Radiocarpal joint CMP joints MCP joints PIP joints Tibiotalar joint Talonavicular joint TMT joints Acromio-clavicular joint	N/A	Axial and longitudinal	In 30% of analyzed joints, vascularity was detected with SMI but not PD ($P = .007$) Out of the joints with vascularity detected on PD and SMI: PD scored better than SMI for conspicuity in 1% of cases; SMI scored better and moderately–markedly better than PD for conspicuity in 73% and 51% of cases, respectively ($P < .001$) Elevated CRP/ESR in 63% of patients with vascular signals on SMI but not PD No vascularity on SMI or PD in asymptomatic joints No vascularity on SMI or PD in controls Inter-observer agreement: ICC = .935
Yokota et al. [26]	Rheumatoid arthritis Other inflammatory arthritides and osteoarthritis	27 patients 12 patients	64 (41–79) 63 (33–86)	To investigate PD and SMI signals in patients with rheumatic diseases To compare the correlation of these signals to clinical and laboratory parameters	PD score SMI score	Wrist MCP joints PIP joints Elbow Knee	Approaches: Dorsal (wrist, MCP, PIP) Anterior (elbow) Anterior, medial and lateral (knee)	Longitudinal	*Rheumatoid arthritis*: Total SMI score was higher than total PD score ($P = .0007$) Prevalence of SMI score 1/0 was higher and lower, respectively, than that of PD in the wrist ($P < .001$) and MCP joints ($P < .05$) No significant difference between PD and SMI in the PIP joints, elbow and knee Total SMI score correlation with CRP ($r = .51/P = .006$) and MMP-3 ($r = .52/P = .006$) Total SMI score correlation with HAQ-DI score ($r = .41/P = .040$) DAS28-CRP correlation with total SMI ($r = .74/P < .0001$) and PD ($r = .57/P = .002$) scores No significant correlation between total PD score and CRP/MMP-3/HAQ-DI *Other arthritides*: no significant difference between SMI and PD total scores Overall inter-observer agreement for SMI: ICC = .95
Yu et al. [27]	Rheumatoid arthritis	26 patients 10 controls	41 (33–68)	To compare SMI and PD for the evaluation of hand joints in patients in clinical remission To demonstrate the value of SMI for identifying true remission	PD score SMI score	Wrist MCP joints PIP joints	N/A	Axial and longitudinal	Remission rate was 65.4% via PD and 42.3% via SMI ($P = .019$) Vascular signals were detected in 18.5% and 8.7% of cases using SMI and PD, respectively ($P < .001$) Compared with PD, SMI increased 18.0% of signals from grade 0 to 1 and 13.7% of signals from grade 1 to 2, but decreased 1.4% of signals from grade 1 to 0 ($P < .01$) Inter-observer agreement for SMI and PD: $K = .463$

Table 1 (continued)

Author date	Disease	Sample (n.)	Patient age (y)	Purpose	Instrumental examination/ parameters evaluated	Scanned region	Approach/ position for SMI assessment	Alignment for SMI assessment	Findings
Lee et al. [23]	Rheumatoid arthritis	56 patients 5 controls	53 ± 18	To evaluate the usefulness of SMI in detecting active synovitis compared with PD To determine its association with clinical manifestation during follow-up	Synovitis (B-mode US) PD score SMI score	Wrist MCP joints PIP joints	Volar/dorsal approach (according to severity)	N/A	The sum of grading for all joints was higher for SMI than PD and B-mode US ($P < .001$) SMI correlated with PD ($\gamma = .878/P < .001$) and B-mode US ($\gamma = .448/P < .001$) SMI and PD respectively correlated with ESR ($\gamma = .409/P = .002$; $\gamma = .458/P < .001$), CRP ($\gamma = .695/P < .001$; $\gamma = .646/P < .001$), VAS ($\gamma = .672/P < .001$; $\gamma = .534/P < .001$) and DAS28-CRP ($\gamma = .726/P < .001$; $\gamma = .646/P < .001$) In 28 patients with clinical remission, SMI sum was higher than PD ($P < .001$) but not significantly different from B-mode US In 17 patients with follow-up (mean 251.6; range 39–642 days), SMI sum was higher compared to PD ($P < .001$) but not significantly different from B-mode US At follow-up, SMI correlated with PD ($\gamma = .860/P < .001$) but not significantly with B-mode US At follow-up, SMI and PD, respectively, correlated with CRP ($\gamma = .645/P = .005$; $\gamma = .628/P = .007$), VAS ($\gamma = .672/P = .003$; $\gamma = .676/P = .003$) and DAS28-CRP ($\gamma = .880/P < .001$; $\gamma = .832/P < .001$); only PD significantly correlated with ESR ($\gamma = .630/P = .007$) No vascularity on SMI in controls
Arslan et al. [20]	Lateral epicondylosis	44 patients 25 controls	42 (24–66)	To compare the diagnostic performance of different US modalities	Swelling, hypoechoic change, tear, calcifications (B-mode US) Elastography strain ratio PD score CD score SMI score	Origin of the common extensor tendon	Elbow semi-flexion	Longitudinal	With a cutoff of score 1 (highest performance), accuracy was 89%, 70% and 63% for SMI, PD and CD, respectively Combination of SMI and B-mode US had the highest accuracy (96%), not improved after further combination with elastography Inverse relationship between SMI and strain ratio ($P < .001$): as softness increases, SMI signal increases in a similar way SMI correlation with symptom duration ($P = .0023$) and VAS score ($P < .001$) SMI signal in 6% of controls Inter-observer agreement for SMI: $K = .71$
Chen et al. [21]	Carpal tunnel syndrome	50 patients 25 controls	55 ± 16	To evaluate the appearance of SMI of the median nerve in patients and controls To compare the diagnostic value of SMI with PD and CD	CSA (B-mode US) PD score CD score SMI score	Median nerve (wrist)	Hand supination and finger semi-extension	Longitudinal	Blood flow display ratio for SMI was higher than that of PD and CD ($P < .005$) CSA ≥ 10.5 mm^2 and/or SMI score ≥ 2 had the highest accuracy (83%, $P < .05$) No significant difference in blood flow display ratio between SMI, PD and CD in controls Inter-observer agreement for SMI: $K = .846$
Karahan et al. [22]	Carpal tunnel syndrome	80 patients	35 (18–45)	To examine intraneural blood flow using SMI and PD To assess PD and SMI correlation with ENMG	ENMG CSA (B-mode US) PD score SMI score	Median nerve (wrist)	Hand supination and finger semi-flexion	Longitudinal	SMI was more sensitive for quantifying intraneural blood flow than PD ($P < .05$) SMI correlation with motor distal latency ($r = .71/P = .026$), amplitude of sensory action potential ($r = -.77/P = .029$) and sensory neurotransmission rate ($r = .77/P = .029$) No significant correlation between ENMG and PD score/CSA

Patient age (years) is approximated to the nearest whole number and expressed as mean (range) or mean ± standard deviation, according to available information

CD color Doppler, *CMC* carpometacarpal, *CRP* C-reactive protein, *CSA* cross-sectional area, *DAS28* disease activity score 28, *ENMG* electroneuromyography, *ESR* erythrocyte sedimentation rate, *HAQ-DI* health assessment questionnaire disability index, *MCP* metacarpophalangeal, *MMP-3* matrix metalloproteinase-3, *N/A* not applicable, *PD* power Doppler, *PIP* proximal interphalangeal, *SMI* superb microvascular imaging, *TMT* tarsometatarsal, *VAS* visual analogue scale

Table 2 Scoring systems adopted for vascularity assessment using SMI and conventional Doppler imaging in different musculoskeletal disorders, according to the current literature

Authors	Disease	Scoring system
Li et al. [28] Orlandi et al. [25] Lee et al. [23]	Rheumatoid arthritis	0: No vascular signal in the synovium 1: Single vascular signal in the synovium 2: Vascular signals in less than half of the area of the synovium 3: More than half of the area of the synovium covered by vascular signals
Lim et al. [24]	Rheumatoid arthritis and other arthritides	0: No difference between SMI and PD 1: SMI detected up to 25% more vessels than PD or vice versa 2: SMI detected 25–50% more vessels than PD or vice versa 3: SMI detected more than 50% of vessels than PD or vice versa
Yokota et al. [26]	Rheumatoid arthritis and other arthritides	0: No vascular signal in the synovium 1: Up to 3 vascular signals in the synovium 2: More than 3 vascular signals in less than half of the area of the synovium 3: More than half of the area of the synovium covered by vascular signals
Yu et al. [27]	Rheumatoid arthritis	0: No vascular signal in the synovium 1: 1–2 vascular signals in the synovium 2: 3–4 short linear vascular signals in less than half of the area of the synovium 3: More than half of the area of the synovium covered by vascular signals
Arslan et al. [20] Karahan et al. [22]	Lateral epicondylosis Carpal tunnel syndrome	0: No vascular signal 1: 1 or 2 focal color-encoded spots 2: 1 linear or more than 2 focal color-encoded spots 3: More than 1 color-encoded linear spots
Chen et al. [21]	Carpal tunnel syndrome	0: No blood flow 1: 1 to 2 spot blood flow 2: More than 2 spot blood flow or 1 to 2 strip blood flow (longer than 1 mm) 3: More than 2 strip blood flow

nine studies share the common purpose of comparing the diagnostic performance of SMI with that of a conventional Doppler technique, such as PD and/or CD. One finding which is constantly seen among the different studies is an increase in vascularity detection using SMI. Additionally, inter-observer agreement for SMI was moderate-to-excellent in the evaluated papers and these data support the fact that it is a reliable and reproducible technique. Conversely, the greatest inhomogeneity among studies regarded the sample size, the assessed parameters and the vascularity interpretation methods. The following paragraphs address the role of SMI in several musculoskeletal disorders, as emerged from our analysis of the current literature.

Rheumatoid arthritis

Rheumatoid arthritis is a chronic systemic inflammatory disease that primarily affects the synovial membrane [29]. The inflammatory process enhances capillary perfusion and permeability, thus determining synovial hyperemia [30]. Doppler US techniques have been largely demonstrated to be excellent in evaluating changes in synovial vascularity resulting from either natural history of the disease or response to therapy [31–33]. Specifically, PD has been reported to improve the accuracy of the 2010 American College of Rheumatology/European League Against Rheumatism classification criteria for rheumatoid arthritis [34]. Owing to its capability of depicting low-velocity flow and minute blood vessels, SMI has the potential to become of major importance in the evaluation and treatment planning of patients with rheumatoid arthritis.

To date, rheumatoid arthritis has received most of the attention regarding SMI, and several studies focused on the assessment of rheumatoid synovitis using SMI (Table 1). Li et al. first compared the diagnostic performance of SMI with that of PD in the assessment of rheumatoid synovitis of metacarpophalangeal and proximal interphalangeal joints [28]. Compared with PD, in a series of 75 patients, SMI increased 18.5% and 60.0% vascularization detectability in patients with active and inactive disease, respectively [28]. Orlandi et al. examined wrist and hand joints in 30 patients with early rheumatoid arthritis or rheumatoid arthritis under treatment with rituximab and demonstrated that SMI detected a higher degree of synovial vascularity compared to PD [25]. Yokota et al. investigated SMI and PD signals in 27 patients with rheumatoid arthritis [26]. Consistently with the two previous papers, they found that SMI was more sensitive to detect active inflammation than PD, particularly in the wrist and metacarpophalangeal joints. Interestingly, this study demonstrated a correlation of serum inflammatory markers and health assessment questionnaire disability index with SMI but not with PD scores [26]. More recently, Yu et al. found SMI to be more sensitive than PD for detecting hand and wrist synovitis in a series of 26 patients with rheumatoid

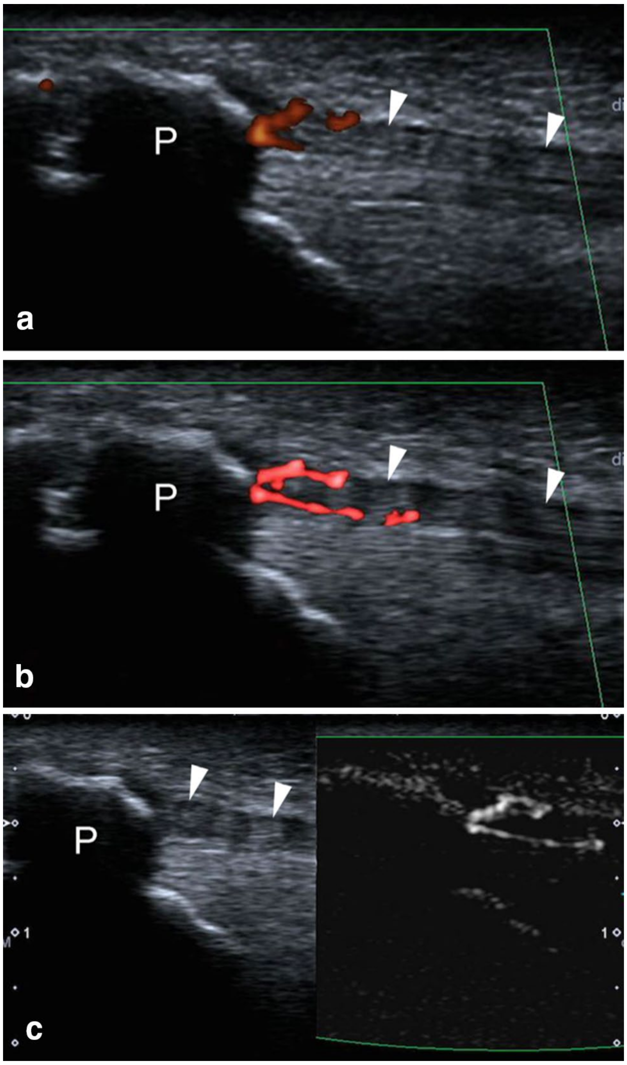

Fig. 2 Jumper's knee (patellar tendinopathy). **a** PD shows hypervascularity of the patellar tendon (arrowheads) at its proximal insertion into the patella (P), **b** in the same patient, color mode SMI and **c** monochrome mode SMI show tendon hyperemia, which consists of two linear vascular signals and is more conspicuous than vascularity detected using conventional Doppler imaging. Color mode SMI and monochrome mode SMI carry the same information

arthritis in clinical remission [27]. Lastly, Lee et al. evaluated hand and wrist joints in 56 patients and reported that SMI correlated with PD and was more sensitive for detection of rheumatoid synovitis, even in the subsets of 28 patients with clinical remission and 17 patients with available follow-up information [23]. Of note, however, these five studies [23, 25–28] used semiquantitative scoring systems based on the absolute quantity of synovial vascular signals that were originally suited for PD (Table 2) [35, 36]. We may speculate this could have resulted in an overestimation of synovial vascularization, as SMI visualizes fine vessels not previously detectable using PD. Hence, some Authors underlined the need for a different scoring system taking into account the different features of SMI compared to conventional Doppler techniques [25, 26]. Differently from the previous authors, Lim et al. did not use an absolute scoring system for vascularity assessment but evaluated PD and SMI signals relative to each other, scanning primarily hand and wrist joints in 19 patients with rheumatoid arthritis [24]. Specifically, when vascular signal was detected on both PD and SMI, its conspicuity was graded with a visual analogue scale comparing these two techniques based on sensitivity and resolution. This study also included patients with other forms of arthritis, and no separate data analysis was provided for them. However, these authors reported that SMI increased overall conspicuity of vascular signal in symptomatic joints in comparison with PD. Of note, there was no vascularity seen on SMI or PD in asymptomatic joints [24]. The main limitations of these studies are the retrospective design of the study by Lee et al. [23] and the lack of follow-up data in the others [24–28]. Hence, future prospective investigations with long-term follow-up are required to validate the role of SMI and properly define its clinical applicability in patients with rheumatoid arthritis.

Other arthritides

The presence of vascularity plays a key role in the evaluation of patients with joint pain and swelling, in particular those patients with some form of arthritis, as increased vascularity indicates active disease [37]. Previous studies showed that, although PD signal is related to active inflammation, the lack of vascular flow on PD cannot reliably exclude disease activity [38–40]. Thus, SMI appears of great value where PD is currently the reference standard for the assessment of active joint inflammation, including inflammatory arthritides and osteoarthritis [41, 42].

According to our review, only a few studies investigated the role of SMI in the assessment of non-rheumatoid synovitis and their findings disagree. Yokota et al. evaluated hand, wrist, elbow and knee joints using a semiquantitative scoring system and found no significant differences between SMI and PD scores [26]. Conversely, Lim et al. proved that SMI was more detectable than PD in the assessment of joint vascularity, scanning primarily hand and wrist joints [24]. Such opposite results may be at least in part due to the lack of distinction between patients with different forms of arthritides, whose results were all reported together. In fact, the study by Yokota et al. comprised, further than those with rheumatoid arthritis, 2 patients with osteoarthritis, 2 with seronegative spondyloarthropathy, 2 with polymyalgia rheumatica, 1 with unclassified arthritis, 1 with systemic lupus erythematosus, 1 with mixed connective tissue disease, 1 with adult-onset Still's disease, 1 with granulomatosis with polyangiitis and finally 1 with sarcoidosis [26]. The study by Lim et al.

included, in addition to those with rheumatoid arthritis, 27 patients with osteoarthritis, 16 with inflammatory arthritis, 9 with psoriatic arthritis and 12 with no definitive diagnosis at the time of study [24]. Further investigations may be aimed to analyze different forms of arthritides separately to understand whether SMI has a major role and clarify its applicability in clinical practice.

Insertional tendinopathy

Insertional tendinopathies are painful overuse-related disorders, in which the capability of the tendons to repair is compromised [43–47]. Microscopic tears occur as a result of mechanical overloading and lead to an abnormal reparative response. Neovessels and accompanying nerves develop in areas of tendinopathy and are responsible for increased pain [48, 49]. This increased vascularity can be detected using conventional Doppler techniques, although some studies suggested that Doppler imaging has yet to reach the desired accuracy rates in visualizing neovessels in tendons [50, 51]. SMI can depict slow-flow fine vessels and then has the potential to improve the results of conventional Doppler modalities in this setting.

According to our review, Arslan et al. compared the diagnostic performance of SMI and other US modalities for diagnosing lateral epicondylosis in 44 patients, using a four-point grading system for SMI [20]. SMI showed to be superior to both PD and CD, and the highest accuracy was reached with the combined use of B-mode US and SMI. Interestingly, they found significant correlation between SMI and the duration of symptoms [20]. Such preliminary findings suggest that SMI may improve diagnostic accuracy for detecting tendon neovascularization; thus, other insertional tendinopathies deserve further investigation.

Entrapment neuropathy

Peripheral nerves are provided by a rich anastomotic system of blood vessels extending from epineuria to fascicles [52, 53]. In the case of entrapment neuropathies, Schwann cell production of vascular endothelial growth factor results in an increased intraneural vascularization [54]. This hypervascularity can be assessed using PD and CD, and Doppler signal has been shown to increase in patients with nerve entrapment in comparison with healthy individuals [55–58]. However, the diagnostic value of conventional Doppler techniques reported in the literature has not been consistent, and contradictory results have been achieved [59–63]. The main reason behind may be that intraneural vessels are fine and blood flow is slow; thus, conventional Doppler techniques may fail to detect true vascularity within the nerve. Thus, SMI may be of great value in the assessment of increased intraneural blood flow resulting from nerve entrapment.

According to our results, only two studies investigated the use of SMI in entrapment neuropathies, focusing on carpal tunnel syndrome. Chen et al. compared the value of SMI with PD and CD in 50 patients with carpal tunnel syndrome, using a semiquantitative scoring system based on richness of vascular signal within the median nerve [21]. The blood flow display ratio (i.e., number of patients with some vascular signal/total number of patients) for SMI was significantly higher than that of PD and CD; then, SMI was more sensitive in demonstrating intraneural vascularity when compared with conventional Doppler imaging. Additionally, B-mode US evaluation of nerve cross-sectional area was combined with SMI, PD and CD, and the highest diagnostic accuracy resulted from combination with SMI [21]. More recently, Karahan et al. examined intraneural vascularity of the median nerve using SMI and PD and assessed their correlation with electroneuromyography parameters in 80 patients with carpal tunnel syndrome [22]. Blood flow images were interpreted using a four-point grading system. This study was in accordance with Chen et al., as SMI was more sensitive for quantifying intraneural vascularity in comparison with PD. Further, electroneuromyography parameters were significantly correlated with SMI grading but not PD findings [22]. In summary, SMI provided better results for the assessment of intraneural vascularity in the median nerve when compared with PD and CD. Further studies using SMI to evaluate the relationship between increased intraneural blood flow and other entrapment syndromes are necessary.

Conclusion

This study is limited to a systematic review of the literature, and no meta-analysis was performed because of the lack of homogeneity between studies in terms of evaluated diseases and parameters. Despite this limitation, in the light of the current literature, SMI may have a great potential for the diagnosis and grading of different musculoskeletal disorders, as well as treatment planning and therapeutic response monitoring. Preliminary studies have shown promising results in patients with rheumatoid arthritis, lateral epicondylosis and carpal tunnel syndrome, where the combined use of SMI and B-mode US achieved the highest diagnostic performance in certain conditions. Further investigations with larger samples of patients and long-term follow-up are warranted.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical standards All performed procedures were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments.

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