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Review

Measurement of vascularity in the scar: A systematic review

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ABSTRACT

Background: Vascularity is an important parameter closely associated with the scar maturation. Reliable and accurate measurement of vascularity helps to monitor the scar change and adopt targeted interventions to prevent excessive scarring and achieve promising outcomes. However, there is no consensus on the assessment tools for the vascularity measurement in scars. This systematic review presents evidence on the available vascularity measurement tools.

Methods: A systematic literature search was done using PubMed, CINAHL, Embase and Science Direct databases. Studies, which used non-invasive measurement tools and explored their clinimetric properties, were identified and included in this review.

Results: A total of 1458 articles were obtained, and 26 articles were finally included in this review. Subjective vascularity measurement scales include the Patient and Observer Scar Assessment Scale (POSAS), the Vancouver Scar Scale (VSS) and the modified Vancouver Scar Scale (mVSS) while objective vascularity measurement devices consist of the color-measuring device, the blood flow measuring device and the morphological imaging device.

Conclusion: Subjective scales are easy to use and have acceptable reliability to give a preliminary impression of the scar vascularity. Three types of objective devices are not equivalent and are mainly based on the blood flow and angiogenesis to quantify the scar vascularity.

Contents

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1. Introduction

Scars can lead to different degrees of functional limitations and psychological difficulties, which further affect survivors' quality of life [1,2]. Various treatments for scar management are currently in clinical use such as pressure therapy, silicone gel sheeting and laser treatment [3,4]. Scar assessment is essential for evaluating and comparing the effectiveness of clinical treatments among different patient groups, and is important for monitoring the progress of scar quality over time.

There are different parameters for scar assessment such as pliability, thickness and pigmentation [5,6]. The measurement of vascularity in the scar is one of the most important scar parameters, which is closely associated with the scar maturation [7,8]. During the wound healing process, newly formed microvascular network and increased capillary blood flow meet the metabolic demand for wound healing and scar formation, and they gradually decrease with scar becoming mature [9]. Therefore, changes in the vascularity are indicators of the scar maturation. Reliable and accurate measurement of vascularity in the scar helps to identify the scar maturation and adopt targeted treatments in the early stage to prevent excessive scarring and achieve promising functional and cosmetic outcomes.

Different types of assessment tools are used to measure the vascularity in the scar. Due to the fact that vascularity is closely related to red blood cells and red blood cells contribute to redness of skin color, most of the assessment tools are based on evaluating the amount of redness in the scar to measure the vascularity [5,10]. For example, the Vancouver Scar Scale (VSS) uses 'normal, pink, red, purple' to rate the scar vascularity. However, it is difficult for scar assessment scales to detect subtle changes of scar color and monitor scar progress resulting from the limitation of naked eyes. Therefore, increasing objective devices are of use in measuring the scar vascularity. As the most commonly used measurement device in clinical settings and research work, the color-measuring device is also based on the scar redness to measure the vascularity. However, poor correlation is reported between the color-measuring device and scar assessment scales [11,12]. It raises the concern about the mechanism of these assessment tools for measurement of vascularity. Additionally, it is known that both the pigmentation and vascularity contribute to the skin color and interfere with each other. It is not clear about the accuracy of vascularity measurement by using these assessment tools.

Other assessment devices measure the scar vascularity based on different theories such as the Laser Doppler Imaging which measures the blood flow. A study reports that the vascularity measurement by the Laser Doppler Imaging is not consistently associated with that by the color-measuring device during the scar maturation process [13]. A recent study also shows that there are no correlations for the vascularity measurement among the immunohistochemistry test, the Laser Doppler Imaging and the color-measuring device [14]. These findings indicate that the assessment tools, which are developed to evaluate the scar vascularity, might measure different scar features. There is no consensus on which available measurement tool has better performance in measuring the vascularity of scars.

This systematic review aims to summarize and compare subjective and objective assessment tools available for the scar vascularity measurement, and looks into their reliability and validity.

2. Methods

2.1. *Data source and search strategy*

A systematic literature search was conducted using PubMed, CINAHL, Embase and Science Direct databases. The following searching terms were used: "(scar OR cicatrix OR fibrosis) AND (evaluation OR evaluate OR assessment OR assess OR measurement OR measure) AND (vascularity OR vascularization OR vascularisation)". The reference lists of potential articles were manually searched to identify additional relevant articles.

2.2. *Inclusion and exclusion criteria*

Articles were identified for this review according to the following inclusion criteria: (1) evaluating the reliability or validity of scales or devices which measure the vascularity in the scar; (2) publishing in English from January 2007 to August 2017. Exclusion criteria included: (1) only using the vascularity measurement results to compare effects of different treatments; (2) only adopting invasive methods; (3) were not human studies; (4) were review papers, books, reports or lectures.

2.3. Data selection and extraction

Two reviewers independently assessed the titles and abstracts of first retrieved articles. Full-text of potentially relevant articles were further read to verify their eligibility based on the inclusion and exclusion criteria. The selection process was shown in Fig. 1. Data extracted from the eligible articles consisted of the number of subjects and raters, the vascularity measurement tools used in the study, the reliability and validity results related to the vascularity measurement.

2.4. Quality assessment

The reliability and validity results were extracted and interpreted using the following criteria.

The reliability is to evaluate the consistency of a measurement tool and there are five different types of reliability reported in this review: (1) the inter-rater reliability is to evaluate the agreement degree for the same subjects among different raters; (2) the intra-rater reliability is to evaluate the agreement degree for the same rater among different trials; (3) the test–retest reliability is to evaluate the consistency degree over time; (4) the internal consistency is to evaluate the agreement degree of different items in the same test; (5) the alternate forms reliability is to evaluate the consistency degree of different versions for the same test. In this review, the Intra-class Correlation Coefficient (ICC), the kappa coefficient, the Spearman's rank correlation coefficient, the Pearson correlation coefficient and the Cronbach's coefficient alpha are used to measure the reliability. An ICC below 0.4 is considered as 'poor agreement', between 0.4 and 0.75 as 'fair to good agreement', above 0.75 as 'excellent agreement' [15]. A kappa coefficient below 0.4 is interpreted as 'marginal agreement', between 0.4 and 0.6 as 'moderate agreement', between 0.6 and 0.8 as 'substantial agreement' and above 0.8 as 'perfect agreement' [16]. The Pearson correlation coefficient is used for the parametric data, while the Spearman's rank correlation coefficient is used for the nonparametric data [17]. Both of them range from −1 to +1, and the larger absolute value indicates the stronger correlation. A Cronbach's alpha above 0.70 is considered as 'acceptable internal consistency' [18].

Only the construct validity is explored in this review, which is to evaluate the degree of a tool measuring what it is purposed to measure. In this review, the construct validity is examined through measuring its correlation with other tools which measure the same construct, or providing evidence that the measurement tool could differentiate subjects with different characteristics. The Kendall rank correlation coefficient is used to present the correlation [19]. The area under the curve (AUC) below 0.6 is considered as 'fail', between 0.6 and 0.7 as 'poor', between 0.7 to 0.8 as 'fair', between 0.8 and 0.9 as 'good', and above 0.9 as 'excellent' [20].

3. Results

A total of 26 articles were included in this review. Based on the vascularity measurement tool that articles purposefully explored, they were classified into two types: (1) subjective vascularity measurement scales including the Patient and

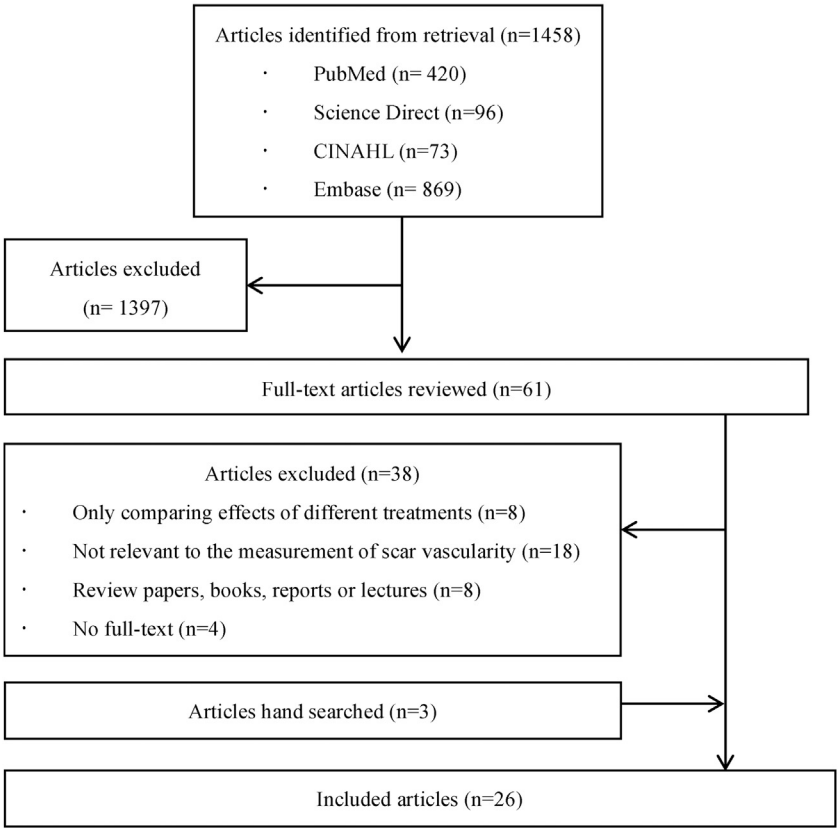

Fig. 1 – Selection process of articles included in this study.

Table 1 – Frequency of the vascularity measurement tools used in included studies.

The vascularity measurement tools	Frequency
Total of included studies	26
Subjective vascularity measurement scales	21
The Patient and Observer Scar Assessment Scale	9
The Vancouver Scar Scale	6
The modified Vancouver Scar Scale	6
Objective vascularity measurement devices	22
The color-measuring device	13
The blood flow measuring device	3
The morphological imaging device	6
The Optical Coherence Tomography	3
The Dermoscopy	2
The Videocapillaroscopy	1

Observer Scar Assessment Scale (POSAS), the Vancouver Scar Scale (VSS) and the modified Vancouver Scar Scale (mVSS); (2) objective vascularity measurement devices including the color-measuring device, the blood flow measuring device and the morphological imaging device. Table 1 summarized the frequency of different vascularity measurement tools used in all the included studies. Tables 2 and 3 summarized the reliability and validity results of different vascularity measurement tools.

3.1. *Subjective vascularity measurement scales*

Five studies explored the reliability and validity of the POSAS [21–25], two studies of the VSS [26,27] and three studies of the mVSS [28–30].

3.1.1. *The Patient and Observer Scar Assessment Scale (POSAS)*

The POSAS was first introduced in 2004 to assess burn scars, which combines the Patient Scar Assessment Scale (PSAS) rated by patients and the Observer Scar Assessment Scale (OSAS) rated by observers [31,32]. The vascularity is measured by observing the amount of redness after pressing and releasing the Plexiglas on the scar.

The vascularity measurement of the POSAS by using photographs or videos showed poor agreement with the on-site assessment (ICC=0.27, 0.11) [21,22]. Mosterd et al. reported fair to good agreement among three raters (ICC=0.648). In addition, they found that the vascularity and pigmentation in the POSAS were the most predictive parameters of the overall scar quality [23]. However, another two studies suggested the pigmentation and pliability [24], and the pliability and relief [25] respectively.

3.1.2. *The Vancouver Scar Scale (VSS)*

The VSS is the first scale used to quantify the pliability, vascularity, pigmentation and height in the scar. By observing the scar at rest and amount of blood refilling after blanching, the vascularity is rated as 'normal, pink, red or purple' [33].

A study compared the method of Equal Appearing Interval (EAI) with the method of Direct Magnitude Estimation (DME) to assess four parameters in the VSS. Regression results showed that the curvilinear function was better than the linear function to present the scar vascularity, which indicated that the current rating method of VSS was not appropriate [27]. For the best parameter contributing to hypertrophic scar diagnosis, a survey suggested the measurement of height in the VSS [26].

3.1.3. *The modified Vancouver Scar Scale (mVSS)*

For the mVSS, one study developed separate vascularity subtest for the Caucasian skin and the Aboriginal skin, and slight agreement was found among raters for the vascularity measurement (k=0.04, 0.12, 0.25) [28]. Another modified version of VSS combined with the Total Body Surface Area (TBSA) showed the moderate to good agreement of the vascularity measurement (k=0.44–0.76) [29]. Simons et al. reported similar results of good to excellent inter-rater reliability of the vascularity measurement in the mVSS (ICC=0.78) as well as in the POSAS (ICC=0.74, 0.75). In this study, correlation coefficients between the on-site assessment and the photographs assessment were 0.55 for the vascularity of POSAS and 0.45 for the vascularity of mVSS respectively [30].

3.2. *Objective vascularity measurement devices*

Three categories of vascularity measurement devices were included in this review, which consisted of the color-measuring device [14,34–40], the blood flow measuring device [13,41] and the morphological imaging device [42–47].

3.2.1. *The color-measuring device*

The color-measuring devices which are based on the principle of reflectance spectroscopy include devices based on the tristimulus reflectance colorimetry and devices based on the narrow-band spectrophotometry. Oxygenated haemoglobin reflects higher percent of red light with absorbing more blue light while de-oxygenated haemoglobin reflects higher percent of blue light with absorbing more red light [48]. Therefore, the color-measuring device measures the reflected light by the scar to quantify the scar vascularity. For devices based on the tristimulus reflectance colorimetry such as the LabScan XE and Spectrophotometer, the indices of a^* is interpreted to measure the vascularity in the scar. For devices based on the narrow-band spectrophotometry such as the DermaSpectrometer and Mexameter, the erythema indices reflect the scar vascularity.

As the most commonly used device for the measurement of scar vascularity, the color-measuring device was explored in eight studies. Three studies explored the reliability and validity of the Mexameter. Acceptable level of agreement was reached for all the measurements (ICC=0.74–0.97) [38,39], and significant correlation was reported between the Mexameter and the vascularity subtest of mVSS (r=0.52–0.65) [38]. However, Seo et al. showed its poor correlation with the vascularity subtest of VSS (r=0.372) [36]. As another type of the color-measuring devices, the color probe of DermaLab Combo showed good to excellent inter-rater reliability for the vascularity measurement (ICC=0.66–0.84) and fair test-retest reliability for the worst scar sites (ICC=0.42), whereas poor test-retest reliability was reported for the best scar sites (ICC=0.29) [37].

A study compared the Mexameter, the Colorimeter which is based on the principle of tristimulus reflectance colorimetry,

Table 2 – Summary of the reliability and validity result for the subjective vascularity measurement scales.

Study	Number of subjects	Number of raters	Vascularity measurement tools	Reliability result	Validity result
1. The Patient and Observer Scar Assessment Scale (POSAS)					
Cai et al. [22]	17 subjects	3 raters	POSAS[a]	Interrater reliability 1) Vascularity (by POSAS): ICC=0.04 (single rater), 95%CI −0.07 to 0.18; $p>0.05$ ICC=0.11 (average rater), 95%CI −0.27 to 0.40; $p>0.05$	N/A
Brolmann et al. [21]	119 subjects	12 raters	OSAS[a]	Alternate forms reliability 1) Agreement between onsite and photographs assessment: ICC=0.27 (vascularity of POSAS), 95%CI 0.09–0.43; p^N	N/A
Mosterd et al. [23]	54 subjects	3 raters	POSAS[a]	Interrater reliability 1) Vascularity (by POSAS): ICC=0.381 (single rater), 95%CI 0.215–0.547; p^N ICC=0.648 (average rater), 95%CI 0.451–0.783; p^N	N/A
Goei et al. [25]	130 subjects	2 raters	POSAS[a]; Dermaspectrometer	Internal consistency 1) OSAS: α^1=0.916 (T3)/0.871 (T>18) 2)PSAS: α^1=0.846 (T3)/0.818 (T>18) Interrater reliability 1) POSAS: ICC=0.950 (T3); 95%CI 0.921–0.969; $p<0.001$ ICC=0.687 (T>18); 95%CI 0.558–0.779; $p<0.001$	Construct validity 1) Correlation between Vascularity (by POSAS) and erythema (by Dermaspectrometer): r^2=0.403 (T3); $p<0.001$ r^2=0.319 (T>18); $p<0.001$ 2) OSAS for long-term scar quality: AUC=0.854 (T3); 95%CI 0.781–0.911; $p<0.001$ 3) PSAS for long-term scar quality: AUC=0.728 (T3); 95%CI 0.640-0.804; $p<0.001$
Eskes et al. [24]	106 subjects	11 raters	POSAS[a]	Internal consistency 1) Vascularity (by POSAS) with overall opinion: r^2=0.32; $p<0.10$	N/A
2. The Vancouver Scar Scale (VSS)					
Brandt et al. [27]	30 scar photos	27 raters	VSS[a]	Intrarater reliability 1) VSS: r^3=0.822 (EAI); p^N r^3=0.809 (DME); p^N Alternate forms reliability 1) Regression analysis of Vascularity (by VSS): $p<0.002$ (r square=0.716 (EAI) vs. 0.866 (DME))	N/A
Thompson et al. [26]	5 scar photos	130 survey responses	VSS[a]	N/A	Construct validity 1) Vascularity (by VSS) for hypertrophic scar diagnosis: AUC=0.78, 95%CI 0.73–0.83; $p<0.001$
3. The modified Vancouver Scar Scale (mVSS)					
Forbes-Duchart et al. [28]	14 subjects	3 raters	mVSS[a]	Interrater reliability 1) Vascularity (by mVSS): k^4=0.12 (R1 vs. R2), 0.04 (R2 vs. R3), 0.25 (R1 vs. R3); $p>0.05$	N/A

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Table 2 (continued)

Study	Number of subjects	Number of raters	Vascularity measurement tools	Reliability result	Validity result
Gankande et al. [29]	30 subjects	3 raters	mVSS[a]	Interrater reliability 1) Vascularity (by mVSS): k_w[5] ('worst' scar)=0.76 (R1 vs. R2), 0.75 (R2 vs. R3), 0.64 (R1 vs. R3); p^N k_w[5] ('best' scar)=0.44 (R1 vs. R2), 0.63 (R2 vs. R3), 0.71 (R1 vs. R3); p^N 2) mVSS: ICC=0.85–0.88 ('worst' scar); p^N ICC=0.65–0.73 ('best' scar); p^N	N/A
Simons et al. [30]	12 subjects	5 raters	mVSS[a]; POSAS	Interrater reliability 1) Vascularity (by POSAS): ICC (mean)=0.74 (onsite), 0.75 (photographs); p^N ICC(single rater)=0.36 (onsite), 0.37 (photographs); p^N 2) Vascularity (by mVSS): ICC (mean)=0.78 (onsite), 0.78 (photographs); p^N ICC (single rater)=0.42 (onsite), 0.41 (photographs); p^N Alternate forms reliability 2) Agreement between onsite and photographs assessment: r^2=0.55 (vascularity of POSAS); p^N r^2=0.45 (vascularity of mVSS); p^N	N/A

[1]: the Cronbach's alpha; [2]: the Spearman's rank correlation coefficient; [3]: the Pearson's correlation coefficient; [4]: the kappa statistic; [5]: the weighted kappa statistic.

[a] The vascularity measurement tool this study purposefully explored; ICC: intra-class correlation coefficient; N/A: not applicable; p^N: p-value is not reported; OSAS: the Observer Scar Assessment Scale; T3: 3 months post-burn; T > 18: at least 18 months post-burn; AUC: the area under the curve; EAI: equal appearing interval; DME: direct magnitude estimation; R1: rater 1; R2: rater 2; R3: rater 3.

and the DSM II ColorMeter which combines the narrow-band spectrophotometry and the tristimulus reflectance colorimetry to measure the vascularity of burn scars. This study supported their reliable inter-rater reliability (ICC=0.84–0.95) and good correlations with the POSAS (r=0.52–0.69) [34]. Kaartinen et al. reported similar result by using a color-measuring device with a modified method (r=0.63) [35].

Of the 26 included articles, a study compared the performance of four different methods to measure the vascularity in the scar consisting of one color-measuring device (DSM II ColorMeter), one blood flow measuring device (Laser Doppler Imaging), one scar assessment scale (POSAS) and the immunohistochemistry test. 32 patients with hypertrophic scars were recruited and assessed. Only significant correlation was found between the DSM II ColorMeter and the vascularity score of POSAS (r=0.403, p=0.03) [14].

3.2.2. *The blood flow measuring device*

The blood flow measuring device adopts a non-invasive way to measure the blood flow in the scar. Light or sound wave is reflected from a dynamic object with frequency change, whereas it reflected from a static object will maintain the same frequency. A color image, in which red and yellow color denotes area with high blood perfusion and the blue color indicates area with low blood perfusion, is generated based on collected signals [49].

Lobos et al. suggested increased vessel thickness, transverse and longitudinal axis, and volume in active keloids comparing with inactive keloids. However, it failed to reach the significant p value [41]. Another study showed inconsistent correlations for the scar vascularity measurement between the Colorimeter and the Laser Doppler Imager at interval of 6 weeks, 3 months, 6 months and 9 months [13].

Table 3 – Summary of the reliability and validity result for the objective vascularity measurement devices.

Study	Number of subjects	Number of raters	Vascularity measurement tools	Reliability result	Validity result
1. The color-measuring device					
Nedelec et al. [38]	32 subjects	3 raters	Mexameter[a]; mVSS	Interrater reliability 1) Erythema (by Mexameter): ICC=0.85 (S1), 95%CI 0.75–0.92; p^N ICC=0.82 (S2), 95%CI 0.71–0.90; p^N ICC=0.97 (D), 95%CI 0.95–0.99; p^N 2) Vascularity (by mVSS): k^4=0.14 (S1); p^N k^4=0.25 (S2); p^N k^4=0.25 (D); p^N	Construct validity 1) Correlation between Erythema (by Mexameter) and vascularity (by mVSS): r^2=0.56 (S1); $p<0.0001$ r^2=0.52 (S2); $p=0.003$ r^2=0.65 (D); $p<0.0001$
Nedelec et al. [39]	30 subjects	1 rater	Mexameter[a]; mVSS	Intrarater Reliability 1) Erythema (by Mexameter): ICC=0.84 (S1), 95%CI 0.72–0.91; p^N ICC=0.74 (S2), 95%CI 0.59–0.86; p^N ICC=0.90 (D), 95%CI 0.83–0.95; p^N	Construct validity 1) Erythema (by Mexameter): $p<0.05$ (324.8±109.98 (scar) vs. 238.56 ±68.17 (normal skin))
Seo et al. [36]	25 subjects	2 raters	Mexameter[a]; VSS	Interrater reliability 1) Vascularity (by VSS): k^4=0.624; p^N	Construct validity 1) Correlation between Erythema (by Mexameter) and vascularity (by VSS): r^3=0.372; $p<0.001$
Gankande et al. [37]	30 subjects	3 raters	DermaLab Combo[a]	Interrater reliability 1) Erythema (by DermaLab Combo): ICC ('best' scar)=0.74 (R1 vs. R2), 95%CI 0.60–0.83; p^N ICC ('best' scar)=0.66 (R1 vs. R3), 95%CI 0.48–0.79; p^N ICC ('best' scar)=0.78 (R2 vs. R3), 95%CI 0.66–0.85; p^N ICC ('worst' scar)=0.84 (R1 vs. R2), 95%CI 0.76–0.89; p^N ICC ('worst' scar)=0.67 (R1 vs. R3), 95%CI 0.50–0.78; p^N ICC ('worst' scar)=0.73 (R2 vs. R3), 95%CI 0.59–0.82; p^N Test–retest reliability 1) Erythema (by DermaLab Combo): ICC=0.42 ('worst' area), 95%CI 0.19–0.58; p^N ICC=0.29 ('best' area), 95%CI 0.01–0.48; p^N	N/A
Gankande et al. [40]	100 subjects	3 raters	DermaLab Combo[a]; mVSS	N/A	Construct validity 1) Correlation between EI% values (by DermaLab Combo) and vascularity (by mVSS): tb^6=0.4 (R1); $p<0.001$ tb^6=0.3 (R3); $p<0.001$
van der Wal et al. [34]	50 subjects	2 raters	Mexameter[a]; Colorimeter; DSM II ColorMeter; POSAS	Interrater reliability 1) Erythema (by Mexameter): ICC=0.90, 95%CI 0.83–0.94; p^N 2) LAB2 (by Colorimeter): ICC=0.95, 95%CI 0.91–0.97; p^N 3) Erythema (by DSM II): ICC=0.84, 95%CI 0.73–0.91; p^N 4) a* (by DSM II): ICC=0.94, 95%CI 0.90–0.97; p^N 5) Vascularity (by POSAS): ICC=0.71 (single), 95%CI 0.54–0.82; p^N ICC=0.83 (average), 95%CI 0.70–0.90; p^N	Construct validity 1) Correlation between Erythema (by Mexameter) and vascularity (by POSAS): r^3=0.59, 95%CI 0.37–0.74; p^N 2) Correlation between LAB2 (by Colorimeter) and vascularity (by POSAS): r^3=0.69, 95%CI 0.51–0.81; p^N 3) Correlation between Erythema (by DSM II) and vascularity (by POSAS): r^3=0.66, 95%CI 0.47–0.80; p^N 4) Correlation between a* (by DSM II) and vascularity (by POSAS): r^3=0.52, 95%CI 0.28–0.70; p^N
Kaartinen et al. [35]	14 subjects	3 raters	SDI and SpM[a]; POSAS; VSS	Interrater reliability 1) Vascularity (by POSAS): ICC=0.51 (1st), 0.56 (2nd); $p<0.05$ 2) Vascularity (by VSS): ICC=0.40 (1st), 0.32 (2nd); $p<0.05$	Construct validity 1) Correlation between Haemoglobin concentration and vascularity (by POSAS): r^2=0.63; $p<0.001$ 2) Correlation between Haemoglobin concentration and vascularity (by VSS): r^2=0.74; $p<0.001$

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Table 3 (continued)

Study	Number of subjects	Number of raters	Vascularity measurement tools	Reliability result	Validity result
Jaspers et al. [14]	32 subjects	3 raters	DSM II ColorMeter[a]; Laser Doppler imaging; POSAS; Immunohistochemistry test	N/A	Construct validity 1) Correlation between Micro-vessel density score (by immunohistochemistry) and blood flow (by LDI): r^3=0.139; p=0.450 2) Correlation between Erythema (by DSM II ColorMeter) and blood flow (by LDI): r^3=−0.115; p=0.551 3) Correlation between Micro-vessel density score (by immunohistochemistry) and erythema (by DSM II ColorMeter): r^3=−0.157; p=0.417 4) Correlation between Erythema difference score (by DSM II ColorMeter) and vascularization score (by POSAS): r^3=0.403; p=0.030
2. The blood flow measuring device					
Lobos et al. [41]	35 subjects	2 raters	Color Doppler ultrasound[a]	N/A	Construct validity 1) Thickness (by CDU): P^7=0.07 (6.5 mm (in active keloids) vs. 3.5 mm (in inactive keloids)) 2) Transverse (by CDU): P^8=0.36 (24.7 mm (in active keloids) vs. 17 mm (in inactive keloids)) 3) Longitudinal (by CDU): P^7=0.76 (25.4 mm (in active keloids) vs. 23.1 mm (in inactive keloids)) 4) Volume (by CDU): P^8=0.41 (3377.1 mm^3 (in active keloids) vs. 1470 mm^3 (in inactive keloids))
Mermans et al. [13]	24 subjects	2 raters	Laser Doppler imager[a]; Colorimeter	N/A	Construct validity 1) Correlation between redness (by Colorimeter) and perfusion (by LDI): r^2 (after 6 weeks)=0.233 (breast scar); p=0.368 r^2 (after 6 weeks)=0.414 (abdominal scar); p=0.099 r^2 (after 12 weeks)=0.622 (breast scar); p=0.002 r^2 (after 12 weeks)=0.353 (abdominal scar); p=0.127 r^2 (after 24 weeks)=0.343 (breast scar); p=0.151 r^2 (after 24 weeks)=0.244 (abdomen scar); p=0.313 r^2 (after 36 weeks)=0.211 (breast scar); p=0.372 r^2 (after 36 weeks)=0.501 (abdomen scar); p=0.029
3. The morphological imaging device					
Liew et al. [42]	8 scar areas	N/A	OCT[a]	N/A	Construct validity 1) Vascular density: 38±3.2% (in scar) vs. 22±1.4% (in normal skin) 2) Median vessel diameter: 34±3.2 μm (in scar) vs. 23±0.7 μm (in normal skin)

Table 3 (continued)

Study	Number of subjects	Number of raters	Vascularity measurement tools	Reliability result	Validity result
Gong et al. [43]	6 scar areas	N/A	OCT[a]	N/A	Construct validity 1) Attenuation coefficient: $p^8 < 0.001$ ($3.8 \pm 0.4\,mm^{-1}$ (in hypertrophic scar) vs. $4.2 \pm 0.9\,mm^{-1}$ (in normotrophic scar) vs. $6.3 \pm 0.5\,mm^{-1}$ (in normal skin))
Gong et al. [44]	13 subjects	N/A	OCT[a]	N/A	Construct validity 1) Birefringence: Ratio = 2.2 (hypertrophic scar vs. normal skin) Ratio = 1.1 (normotrophic scar vs. normal skin) 2) Median birefringence ratio: $p^8 < 0.001$ ((hypertrophic scar to normal skin) vs. (normotrophic scar to normal skin))
Yoo et al. [45]	41 subjects	N/A	Dermocopy[a]	N/A	Construct validity 1) Vascular structures (arborizing): OR = 8.750 (keloid scars vs. hypertrophic scars); $p = 0.033$ 2) Vascular structures (linear irregular): OR = 4.286 (keloid scars vs. hypertrophic scars); $p = 0.238$ 3) Vascular structures (comma-shaped): OR = 1.538 (keloid scars vs. hypertrophic scars); $p = 1.000$
Wei et al. [46]	18 subjects	2 raters	Dermoscopy[a]; Spectrocolorimeter; VSS	Interrater reliability 1) Redness (by Dermoscope): ICC = 0.930, 95%CI 0.842–0.969; $p < 0.01$ Test-retest reliability 1) Redness (by Dermoscope): ICC = 0.980, 95%CI 0.964–0.989; $p < 0.01$	Construct validity 1) Correlation between redness (by Dermoscopy) and redness (by spectrocolorimete): $r^3 = 0.890$(mean), 0.891(R1), 0.881(R2); $p < 0.01$ 1) Correlation between redness (by Dermoscope) and vascularity (by VSS): $r^2 = 0.625$; $p < 0.01$
Gangemi et al. [47]	12 subjects	2 raters	Videocapillaroscopy[a]; VSS	N/A	Construct validity 1) Capillary diameters: $p^8 = 0.04$ (20.5 μm (AHS) vs. 16.2 μm (control)) $p^8 < 0.01$ (16.2 μm (RHS) vs. 12.4 μm (control)) $p^8 > 0.05$ (14.6 μm (NT) vs. 12.0 μm (control)) 2) Capillary length: $p^8 = 0.03$ (467.2 μm (AHS) vs. 241.0 μm (control)) $p^8 < 0.01$ (443.4 μm (RHS) vs. 287.4 μm (control)) $p^8 = 0.01$ (398.8 μm (NT) vs. 272.1 μm (control)) 3) Neoangiogenesis ('bush-like'/'deer horn-like'): $p^9 < 0.01$ (AHS: 3.04 vs. 0.15) $p^9 = 0.01$ (RHS: 1.02 vs. 0.09)

[1]: the Cronbach's alpha; [2]: the Spearman's rank correlation coefficient; [3]: the Pearson's correlation coefficient; [4]: the kappa statistic; [5]: the weighted kappa statistic; [6]: the Kendall tau-b rank correlation; [7]: the Wilcoxon–Mann–Whitney test; [8]: the student's t-test; [9]: the x^2 test.

[a] The vascularity measurement tool this study purposefully explored; ICC: intra-class correlation coefficient; N/A: not applicable; p^N: p-value is not reported; SDI and SpM: standardized digital imaging and spectral modelling; S1: the most severe scar site; S2: the less severe scar site; D: donor; EI%: erythema index%; R1: rater 1; R2: rater 2; R3: rater 3; CDU: color Doppler ultrasound; LDI: laser Doppler imager; OCT: Optical Coherence Tomography; OR: odds ratio; AHS: active hypertrophic scar; RHS: remitted hypertrophic scar; NT: normotrophic scar; VSS: Vancouver Scar Scale; mVSS: modified Vancouver Scar Scale; POSAS: Patient and Observer Scar Assessment Scale.

3.2.3. *The morphological imaging device*

The Optical Coherence Tomography (OCT), the Dermoscopy and the Videocapillaroscopy are three types of devices based on morphological imaging technique, and they are used to measure the scar vascularity in recent years.

The OCT measures the echo delay time and magnitude of backscattered or back-reflected light to generate 3D images of tissue microstructure. Significant differences were found in vascular density and vessel diameter [42], attenuation coefficient [43] and birefringence ratio [44] among hypertrophic scars, mild scars and normal skin.

The Dermoscopy is a portable device which non-invasively uses optic magnification to present vascular structure in the tissue. It was found that frequency of arborizing vascular structure significantly differed between in keloid scars and in hypertrophic scars [45]. Additionally, excellent inter-rater (ICC=0.93) and test-retest reliability (ICC=0.98), and strong correlations with other vascularity measurement tools (r=0.625–0.891) were reported for the Dermoscopy [46].

Only one study in this review used the Videocapillaroscopy which provides a direct way to observe microvascular structures of tissue. Comparing with normal skin, significant increase of capillary loop diameter and length, and specific vascular structures were identified in scars [47].

4. Discussion

This is the first systematic review to summarize subjective and objective assessment tools for the measurement of vascularity in the scar which is a vital indicator of the scar maturation [8].

All the three subjective assessment scales measure the scar vascularity through evaluating the amount of redness in the scar. The Plexiglas is used to blanch the scar which decreases the influence of scar pigmentation on the vascularity judgment [50]. Acceptable inter-rater reliability of the VSS [27], the mVSS [29,30] and the POSAS [23,30] are reported for the measurement of vascularity. Because of their easy to use, subjective assessment scales are widely implemented in clinical settings to preliminarily evaluate the scar. The VSS is the first used assessment scale. However, increasing evidence suggests its irrelevant and nonspecific scar component measurement, poor reliability and difficult use for identifying scar progress [5,26,51]. As a newly developed assessment scale, the POSAS rates the scar vascularity from 1 to 10, which is more sensitive than the VSS to identify scar changes. In addition, patients' perception is involved into the assessment and provides reference for individualized plans of scar management.

In this review, using photographs to evaluate the scar vascularity in the POSAS shows poor agreement with on-site assessment results [21,22]. The vascularity measurement is a dynamic process of observing the blood refilling after blanching the scar, however, photographs only present static images of scar color and it is difficult for raters to distinguish the scar vascularity from the pigmentation especially for the scar with hyper-pigmentation and increased vascularity at the same time [12,28]. For future vascularity measurement by using photographs, taking a short video is recommended to show the process of scar redness change after using the Plexiglas, and attention should be paid to the environment lighting, setting up of camera and quality of internet which potentially affect the quality of photographs or videos. Some scales are specifically developed for the scar photograph assessment such as the Manchester Scar Scale, the Yeong's Burn Scar Assessment and the Hamilton Scar Rating Scale. However, limited evidence reports the reliability and validity to support their use in clinical and research work [52].

As the most commonly adopted assessment device, the color-measuring device could quantitatively measures the amount of skin redness to present the scar vascularity. Our review supports that the color-measuring device provides reliable measurement results among raters and provides continuous numerical data which is more sensitive than scar assessment scales to detect subtle changes over time [34,37–39]. Acceptable correlations are also reported between the color-measuring device and the mVSS [38,40], the VSS [35] or the POSAS [14,34,35] separately. However, two studies report weak correlation with the assessment scale [36] and non-significant correlation with other vascularity measurement devices [14]. As a commonly reported limitation, the color-measuring device with open chamber is easily affected by the environment lighting and hair. Therefore, it is suggested to trim the hair before the color measurement and control the environment lighting during the assessment process. Given that pressure on skin will change the skin color, raters are required to lightly put the color-measuring device in contact with scars without causing additional pressure. To reduce the influence of pressure, some devices provide a spring in the probe head such as the Mexameter to ensure constant pressure on the skin. Another limitation of the color-measuring device is their limited measurement area at one time caused by the small size of probe, which increases the difficulty in comprehensively presenting the color of a large size scar and in applying to patients with large burned area.

The blood flow measuring device which has been proved useful in evaluating the burn depth and skin inflammation [53,54] depends on the velocity and concentration of red blood cells to quantify the scar vascularity. Studies suggest that more active scars are associated with increased blood perfusion [13,41]. However, these two studies fail to give reference scores to show scars in different stages. It is worthwhile for future studies to explore the blood perfusion in different stage scars as well as normal skin. It will give a clear clue of the blood perfusion change during the scar maturation process. Because of the high sensitivity of skin perfusion to external stimulation and changes in body temperature and breathing movement [49], it is vital to follow a standardized protocol to measure the scar vascularity by using the blood flow measuring device such as guiding patients to remove pressure garment and sit on a chair for rest 20 min prior to the assessment, as well as keeping a consistent temperature and humidity of the assessment room.

With increasing concern about the safety of measurement tools, the morphological imaging technique is developed as an alternative to biopsy. Our results support its feasibility of measuring the vascularity to distinguish scars from normal skin [42–44,47] or from keloid scars [45]. However, the reliability is only explored for the Dermoscopy and the result indicates its good inter-rater and test-retest reliability [46].

The penetration depth and resolution decide on the performance of morphological imaging devices to measure the scar vascularity. The OCT was firstly utilized in ophthalmology for identifying eye diseases and has become increasingly used in dermatology to image the microvasculature of skin tissue. The penetration depth of the OCT is approximately 2 mm with the resolution of 4–10 μm [55]. Both the Dermoscopy and the Videocapillaroscopy are based on the theory of magnification. Therefore, their penetration depth is limited to the superficial layer of skin. The Dermoscopy can provide the magnification of up to 70 fold while the Videocapillaroscopy provides greater magnification of 200–600 fold. The Dermoscopy lacks the micrometer-scale resolution to distinguish individual capillary vessels and is generally used to identify the presence of specific vascular pattern such as comma-shaped pattern [56], while the capillary length and diameter can be measured by using the Videocapillaroscopy. With technology development, some new versions of Dermoscopy adopt the cross-polarized light which allows more light pass through the stratum corneum till the dermis [57].

Cost and portability are closely related to the utilization of devices in clinical settings. Comparing with low cost of the Dermoscopy (around USD 2000), the cost of the OCT (around USD 40,000) and the Videocapillaroscopy (around USD 37,000–70,000) are much more expensive [58]. High sensitivity to motion resulting in distortion of images and dependence on system further limit the portability of OCT. Comparing with the OCT, handheld Dermoscopy and Videocapillaroscopy are more convenient for clinical and research use.

Evidence demonstrates that increased blood flow and angiogenesis take place during the wound healing and scar formation process [59]. Angiogenesis refers to the process of growing new blood vessels [60]. For objective vascularity measurement tools, the color-measuring device measures the reflected light by the haemoglobin in vessels, the blood flow measuring device evaluates the blood flow, and the morphological imaging device assesses the angiogenesis to quantify the vascularity in scars. Therefore, the three types of devices are not equivalent for the measurement of scar vascularity. Comparing with the blood flow which is easily affected by the environment and stimulations, the angiogenesis is more stable for measurement. More importantly, our results support the feasibility of differentiating scars from normal skin or from keloid scars by using the morphological imaging device. It is worthwhile for future studies to explore its ability of predicting the scar maturation to further support the use of morphological imaging devices.

5. Conclusion

This review presents available evidence on subjective and objective scar vascularity measurement tools. Because of acceptable reliability and easy to use, subjective vascularity measurement scales are widely used to give a preliminary impression of the scar vascularity. With a more sensitive rating method and involvement of patients' perception, the POSAS is recommended. For objective vascularity measurement devices, the color-measuring device measures the amount of scar redness with reliable readings and sensitive measurements. The blood flow measuring device assesses the blood flow and indicates that more active scars are related to increased blood perfusion. The morphological imaging device evaluates the angiogenesis and demonstrates its feasibility of differentiating scars from normal skin or from keloid scars.

Conflicts of interest

The authors confirm that there are no known conflicts of interest.

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