

Quantitative Image Analysis of Vascular Skin Response to Intense Pulsed Light Therapy

Aleksandra Lipka-Trawińska¹, Anna Deda², Barbara Błońska-Fajfrowska³, Agata Lebieadowska³,
Magdalena Hartman-Petrycka³, Robert Koprowski⁴, Dominika Wcisło-Dziadecka², Sławomir Wilczyński³

¹Clinical Department of Dermatology, Department of Internal Medicine, Dermatology and Allergology, Faculty of Medical Sciences in Zabrze, Medical University of Silesia in Katowice, Zabrze, Poland; ²Department of Practical Cosmetology and Skin Diagnostics, Faculty of Pharmaceutical Sciences in Sosnowiec, Medical University of Silesia in Katowice, Sosnowiec, Poland; ³Department of Basic Biomedical Science, Faculty of Pharmaceutical Sciences in Sosnowiec, Medical University of Silesia in Katowice, Sosnowiec, Poland; ⁴Institute of Biomedical Engineering, Faculty of Science and Technology, University of Silesia, Sosnowiec, Poland

Correspondence: Agata Lebieadowska, Department of Basic Biomedical Science, Faculty of Pharmaceutical Sciences in Sosnowiec, Medical University of Silesia in Katowice, Jedności 8B, Sosnowiec, 41-208, Poland, Tel +48 269 98 30, Email alebieadowska@sum.edu.pl

Purpose: This study assessed the effectiveness of treatments using intense pulsed light (IPL) in reducing vascular lesions of the facial skin, such as erythema and telangiectasia.

Patients and Methods: The study involved 38 subjects aged 20 to 61 who underwent a series of 3 IPL procedures. In order to quantitatively assess the effects of therapy, advanced clinical photography techniques involving cross-polarized light and dedicated image analysis algorithms, ie GLCM (Gray-Level Co-occurrence Matrix) and QTDCOMP (Quadratic Tree Decomposition), were used.

Results: The results indicate a significant reduction in vascular lesions after a series of treatments, which was confirmed by a statistically significant reduction in GLCM contrast and an increase in image homogeneity. Additionally, the use of quadratic tree decomposition allowed for the quantitative determination of skin homogeneity after therapy.

Conclusion: The study has shown that image registration in cross-polarized light as well as GLCM and QTDCOMP analysis are effective tools for the objective and quantitative assessment of vascular skin lesions. These methods can be widely used in clinical practice to optimize the therapy of vascular lesions and monitor the effectiveness of IPL procedures.

Keywords: vascular lesions, cross-polarized light, image analysis, homogeneity, quantitative evaluation

Introduction

Vascular skin is characterized by telangiectasia and erythema, which may also be accompanied by swelling.¹ In selected physiological conditions, such as pregnancy, dermatological and systemic diseases, erythema and telangiectasia may also occur. UV radiation, wind, low ambient temperature, use of stimulants and inappropriate skin care contribute to the exacerbation of vascular lesions.

Diagnostics of vascular skin include: physical examination, non-invasive instrumental techniques and - less frequently - advanced invasive methods, such as biopsy and provocative skin tests. Physical examination of the skin determines the severity of symptoms (erythema or telangiectasia). Unfortunately, there are no standardized criteria in this regard.² Moreover, visual clinical examination is a subjective method, and the results of the assessment of lesions may largely differ depending on the examiner's "eye".³ In scientific research, there is a need for objective, non-invasive quantitative assessment of skin pigmentation. The instrumental methods of skin colour analysis include spectrophotometry, dermatoscopy, chromatometry, capillaroscopy, and clinical photography.⁴

Photographic documentation plays an invaluable role in assessing the effectiveness of procedures, both qualitatively and quantitatively, when combine with dedicated image analysis.⁵ It is essential for the objective evaluation of treatment outcomes. However, for this purpose, the images must be comparable and standardized.^{6,7} There are ready-made systems on the market that make it possible to record highly repeatable photographs of excellent quality. Such devices most often consist of a camera

integrated with a lighting system, a filter system and a patient positioning system. Specialized techniques such as polarized light photography and fluorescence photography help document specific skin lesions. Polarizing filters are used to reduce light reflection by removing both the glare of reflected lamp light and the shininess on the skin surface caused by sweat and sebum. Cross-polarizing filters improve lesion visibility and increase contrast with unaffected skin.^{8,9} In cross-polarized light, polarizing filters are used in both the camera lens and the flash to selectively improve surface features (such as fine lines and wrinkles, enlarged sebaceous glands, scars) or subsurface features (such as erythema, pigmentation changes). This is achieved by rotating one of the two linear filters so that its orientation is perpendicular to the orientation of the other filter.⁸ To assess inflammatory lesions, cross-polarized light photography is most often used. This method allows for the visualization of subsurface features, eg post-inflammatory discoloration, as well as the intensity and degree of erythema. After obtaining the images, ROIs (region of interest) need to be extracted and then the green channel of the RGB image must be isolated. In the green channel image that has been converted to a grayscale image, erythema is in black and unchanged skin in white.^{8,9}

Skin colour analysis enables determination of erythema severity and assessment of treatment response through changes in colour dynamics and intensity.¹⁰ Colour information can be acquired and transmitted in various ways. Colour models are applied to describe colours used in digital graphics. Each colour model has its own colour space, and therefore its own range of colours that can be obtained and its own way of creating and identifying them. The RGB model results from the properties of the human eye, in which the perception of any colour can be created by mixing three light beams in fixed proportions: red, green and blue. RGB is one of the most commonly used colour spaces for digital image processing. It is an additive model, in which secondary colours are obtained by mixing the primary colours: R (red), G (green) and B (blue) in various proportions. Most often, the RGB model takes the 24-bit form, in which each of the 8-bit components can change its value from 0 to 255. When all the components take the value of 255, the colour is white. The point (0,0,0) corresponds to black. The colours placed between these points correspond to different shades.¹¹

It should be emphasized that simply taking a standardized photo of skin lesions, including erythema, is only half the success. To quantitatively determine the lesion severity, it is necessary to use appropriate, dedicated image analysis and processing algorithms. These algorithms should be adapted as much as possible to the physiological factors responsible for the formation of erythema and the perception of erythema. For example, identifying erythema itself: segmenting vascular lesions (isolating them from the background), determining the colour of lesions and the number of lesions per unit area, will not make it possible to determine whether the lesion is very or slightly severe. This is due to the fact that the perception of lesions by the human eye is much more complicated. For example, if a patient has a very low phototype and the colour of vascular lesions is relatively dark, the lesions will be subjectively perceived as very severe. In turn, if the skin has a high phototype and the lesions are dark, they will not be subjectively assessed in such a negative way. That is why, vascular lesions like any other skin lesions should be quantitatively identified in the broad context of physiological parameters of the skin. Therefore, this study aimed to develop and adapt image analysis algorithms enabling quantitative assessment of skin vascular response to high-energy light treatments.

In our study we moved beyond single-channel brightness metrics, as they ignore spatial context. Contemporary reviews of erythema assessment note that such per-pixel colorimetric measures are sensitive to illumination and skin-type variability and often miss clinically meaningful pattern changes.¹² GLCM directly addresses this by quantifying the spatial co-occurrence of gray levels—capturing local textural contrast and homogeneity that govern how erythema and telangiectasia are perceived. This allows detection of treatment-related changes in lesion visibility even when mean intensity remains unchanged. GLCM features have already been applied to track cutaneous treatment effects in clinical studies, supporting their robustness for objective and repeatable before–after comparisons.¹³ QTDCOMP (quad-tree decomposition) complements GLCM by testing image uniformity hierarchically across spatial scales. This approach is well-suited to vascular lesions, which often evolve from fine, irregular islands toward larger, more uniform regions after effective therapy. Quad-tree methods are established in medical imaging for multi-resolution region analysis and edge localization, offering a structured way to summarize heterogeneity that simple threshold or brightness approaches cannot.¹⁴ Together, GLCM (local texture statistics) and QTDCOMP (multi-scale homogeneity) position our pipeline within the broader landscape of objective image-based vasculature assessment as a low-cost, camera-based alternative that preserves spatial information often lost in traditional colorimetric indices, while remaining far easier to deploy than spectroscopy or hyperspectral systems.¹²

Similarly, quadratic tree decomposition (QTDCOMP) is a method of image analysis that iteratively divides an image into smaller regions based on predefined brightness thresholds. This approach makes it possible to identify areas of greater or lesser homogeneity by quantifying how image uniformity changes at different spatial scales. The rationale for applying QTDCOMP in the assessment of vascular skin lesions is that erythema and telangiectasia typically appear as irregular, heterogeneous regions, while effective therapy should lead to larger, more uniform skin areas. Therefore, QTDCOMP complements GLCM by providing a scale-sensitive evaluation of image homogeneity. To achieve the research goal, it was necessary to:

- Develop a methodology for acquiring skin images in visible light in a repeatable manner, enabling an objective assessment and comparison of the skin condition before and after a series of treatments,
- Verify the hypothesis regarding the clinical effectiveness of treatments using IPL to reduce vascular lesions within the face,
- Verify the hypothesis regarding the advantage of recording images in cross-polarized light over recording images in unpolarized light for the quantitative analysis of vascular lesions.

Materials and Methods

Study Participants

The initial study included 38 subjects aged 20 to 61 with erythematous lesions, vascular skin and/or rosacea. The characteristics of the volunteers and their previous treatments are presented in Table 1. The research was carried out after obtaining the written consent from the study participants, who were familiarized with the purpose of the research and its course, and the consent of the Ethics Committee of the Medical University of Silesia No. PCN/0022/KB1/11/I/20 of May 19, 2020. The study was conducted in accordance with the principles of the Declaration of Helsinki. The inclusion criteria were: voluntary participation and presence of

Table 1 Characteristics of Volunteers Participating in the Study

Participant Number	Age	Gender	Skin Type (Fitzpatrick Scale)	Topical Medications	Oral Antibiotics	Isotretinoin
1	23	Female	II	Yes	No	No
2	30	Male	II	Yes	No	No
3	32	Female	II	Yes	Yes	Yes
4	21	Female	III	Yes	No	No
5	56	Female	II	Yes	Yes	Yes
6	57	Female	II	Yes	Yes	No
7	61	Female	II	Yes	Yes	No
8	27	Female	II	Yes	Yes	No
9	33	Female	II	Yes	No	No
10	37	Male	II	Yes	Yes	No
11	36	Female	II	Yes	No	No
12	42	Female	II	Yes	Yes	Yes
13	45	Female	II	Yes	Yes	No
14	46	Female	II	Yes	Yes	No
15	52	Female	II	Yes	Yes	No
16	55	Female	II	Yes	Yes	Yes

(Continued)

Table I (Continued).

Participant Number	Age	Gender	Skin Type (Fitzpatrick Scale)	Topical Medications	Oral Antibiotics	Isotretinoin
17	28	Female	II	Yes	No	No
18	29	Female	II	Yes	Yes	No
19	32	Female	II	Yes	Yes	No
20	25	Female	III	Yes	No	No
21	27	Female	II	Yes	No	No
22	45	Female	II	Yes	Yes	No
23	56	Male	II	Yes	Yes	Yes
24	59	Male	II	Yes	Yes	Yes
25	37	Female	II	Yes	Yes	No
26	60	Female	II	Yes	Yes	No
27	43	Female	II	Yes	Yes	Yes
28	42	Female	II	Yes	No	No
29	39	Female	III	Yes	Yes	No
30	28	Female	II	Yes	No	No
31	22	Female	II	Yes	No	No
32	29	Female	II	Yes	Yes	No
33	45	Female	II	Yes	Yes	No
34	43	Female	II	Yes	Yes	No
35	29	Male	II	Yes	Yes	No
36	59	Male	II	Yes	Yes	Yes
37	61	Female	II	Yes	Yes	No
38	48	Female	II	Yes	Yes	No

skin lesions qualifying for high-energy light treatments (vascular lesions such as erythema and/or telangiectasia on the face - qualification conducted by a dermatologist). Skin phototypes II or III. The exclusion criteria were: patient's age below 18 years of age, susceptibility to keloids and hypertrophy of scars, implanted pacemaker or defibrillator, untreated diabetes, fresh tan, viral, bacterial and fungal diseases of the skin, use of drugs or herbs with photosensitizing properties, pregnancy and lactation, cancer, taking anticoagulants, vitiligo, tattoo, permanent makeup in the treatment area, superficially applied fillers in the last 6 months and botulinum toxin in the last 2 weeks, surgical procedures in the treatment area in less than 3 months, no/withdrawal of consent to participate in the research.

Image Acquisition with the Fotomedicus System

The FOTOMEDICUS system from Elfo, Poland, was used to acquire skin images and determine the severity of vascular lesions. It is a device with compatible software that makes it possible to take photographs with precisely defined parameters, which ensures the creation of repeatable medical documentation.¹⁵ The photo background is white homogeneous texture sized 70x200cm. The Fotomedicus system allows for the acquisition of images in unpolarized and cross-

polarized light for a polarization angle $\theta = 90^\circ$. The photos were taken twice, before a series of treatments and after 3 erythema reduction procedures using polychromatic light (IPL).

The Course of Erythema Treatment

The treatments aimed at reducing erythema were performed using the Lumecca device, Inmode, (USA). Each of the 38 subjects underwent 3 procedures involving polychromatic light. The treatment parameters were selected individually, based on the reaction of the skin (blood vessels) after emitting an impulse with specific energy density.

Statistical Analysis

Excel and Statistica 10 were used for statistical analysis of the results. The significance of the impact of treatments on the number of squares with specific sides was assessed using the Wilcoxon test. The change in the number of squares with sides 2×2 , 4×4 , 8×8 , 16×16 and 32×32 , 64×64 pixels, occurring under the influence of treatments, was illustrated by calculating the percentage of the median value of individual squares in relation to the sum of the medians of these squares. The significance of the effect of treatments on the GLCM contrast and homogeneity and the mean value calculated based on histograms was assessed using the Student's *t*-test for related data. The value of $p < 0.05$ was considered statistically significant. The normality of the distribution of results was tested using the Shapiro–Wilk test - homogeneous variances (Leven's test). In the case of the normal distribution of results, it was possible to use a *t* test for dependent samples to determine the effect of the treatment. However, in the absence of normal distribution, the Wilcoxon signed-rank test was used to compare the treatment parameters before and after IPL procedures.

Results

Image Pre-Processing

The first stage of research, related to image analysis and processing, was the separation of recorded images in RGB space into individual channels: red, blue and green. RGB decomposition was performed using ImageJ 1.52a version. At the same time, both the output image (RGB) and its individual channels were transformed into grayscale images. Transformation to grey levels was performed in Matlab Version 7.11.0.584 (R2010b), 2018.

The next stage of image processing involved the normalization of the obtained images. Normalization, ie expanding the dynamic range, aims to increase the contrast of the analysed images. In the recorded images, the brightest image points were not white and the darkest were not black, so the entire dynamics of the system was not used. The effect of the normalization operation is the expansion of the grey range in the examined image to the full range of shades of grey. Normalization was performed for the entire set of images (a total of 1520 images were recorded) and consisted in identifying the brightest pixel in the entire set of images, which was assigned a brightness of 255, and the darkest pixel in the set of images, which was assigned a brightness of 0. Appropriate grey levels in the range 0–255 were assigned to the remaining pixels.

Figure 1 shows images of the ROI (region of interest) marked in subject No. 1, recorded in cross-polarized light, before and after 3 IPL procedures, respectively. Even a cursory visual analysis of the images indicates a significant reduction in erythema. All images were coded prior to analysis so that the investigator performing GLCM and

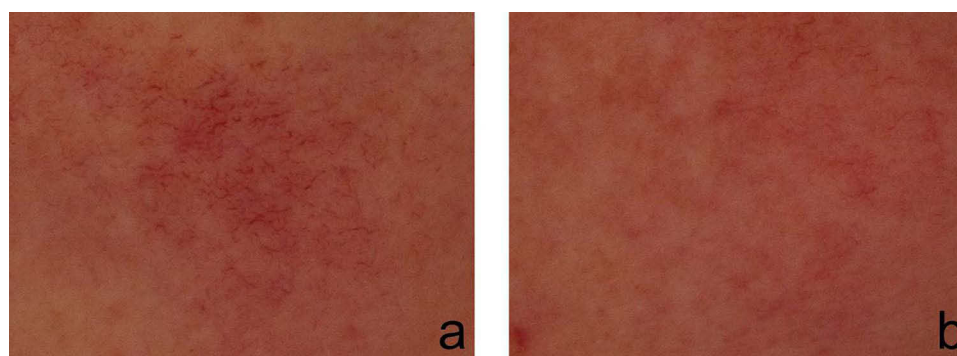


Figure 1 ROI marked in subject No. 1 - before the first procedure (a) and after the third IPL procedure (b). The photos were taken in cross-polarized light.

QTDCOMP calculations was blinded to the treatment status (pre- or post-therapy) and to the treated side. Image analysis was performed using predefined algorithms in ImageJ and Matlab, minimizing the influence of operator bias.

GLCM Analysis

Figure 2 shows the mean GLCM contrast for ROIs of RGB images converted to grey levels. In all analyses, GLCMs were computed on ROIs after channel-wise RGB separation and global normalization to 8-bit grayscale (0–255) in MATLAB R2010b. Contrast and homogeneity features were extracted using adjacent-pixel offsets of one pixel at 0° (horizontal direction). These parameter choices are standard in skin-texture GLCM analyses aimed at capturing short-range vascular structure and have been recommended in methodological overviews of dermatologic and biologic imaging. Consistent with our pipeline, we report results both for the grayscale composite and for each RGB channel processed to gray levels, all using the same GLCM offset. Conversion to grey levels was necessary to normalize the image series. GLCM contrast analysis (Figure 2) indicates a statistically significant reduction in GLCM contrast of the ROI after a series of treatments: from 7.1 to 6.5.

Figure 3 shows the mean GLCM contrast for the ROIs for all subjects for the individual image channels, red, green, and blue, respectively. The highest contrast before a series of treatments for ROIs for all tested subjects was recorded for

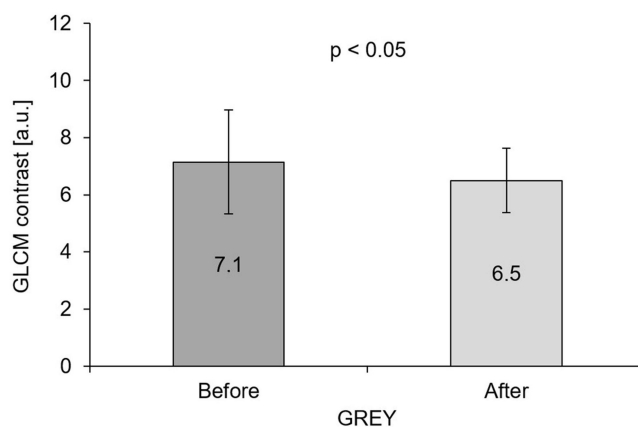


Figure 2 Mean GLCM contrast for images analysed in the RGB space of the ROI after conversion to grey levels before the first procedure and after the third IPL procedure.

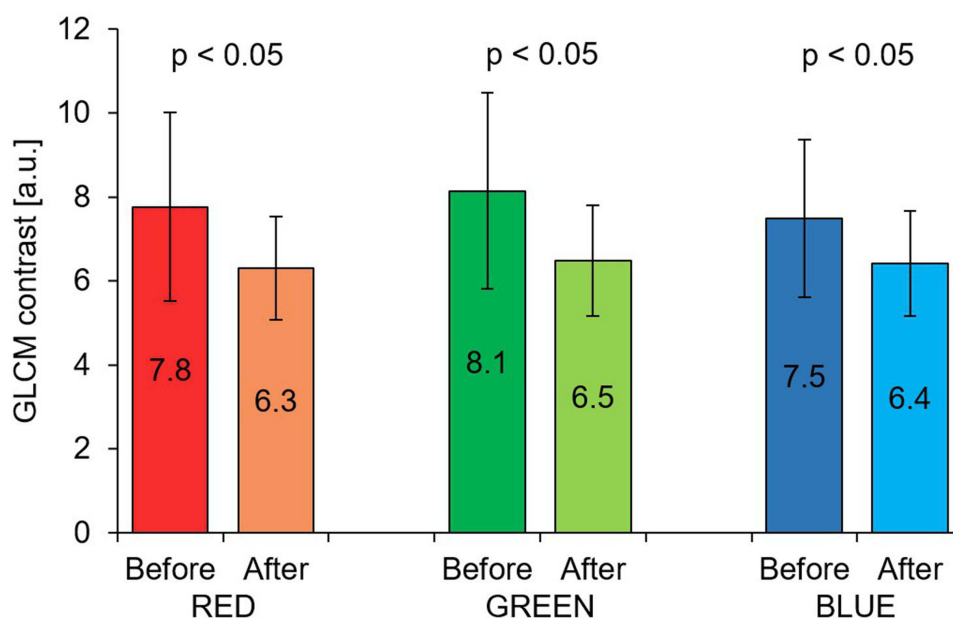


Figure 3 Mean GLCM contrast of ROI images for all participants for the red, green, and blue channels before the first procedure and after the third IPL procedure.

the green channel (8.1), and the lowest for the blue channel (7.5). It should be noted that for all three image channels, ie red, green and blue, the mean GLCM contrast after a series of procedures decreased. The highest GLCM contrast decrease was recorded for the green channel (19.8%).

In addition to GLCM contrast, GLCM homogeneity was also identified in the recorded images. It is a measure of image uniformity: the higher the homogeneity, the less severe the vascular lesions. Figure 4 shows the mean GLCM homogeneity for all subjects before and after a series of 3 IPL procedures. Figure 5 shows the differences in GLCM homogeneity before and after IPL procedures for the red, green and blue channels. Both in the case of homogeneity identified in the RGB image and for individual red, green and blue channels, this parameter increased statistically significantly after a series of treatments.

The left cheek is characterized by higher mean homogeneity of the initial RGB images (before a series of treatments). This confirms the results obtained for the GLCM contrast, which indicate that the left side of the face is slightly less

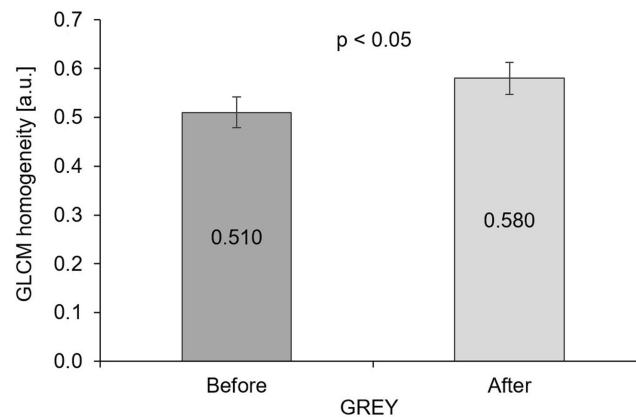


Figure 4 Mean GLCM homogeneity for RGB images of ROIs for all study participants after conversion to grey levels before the first procedure and after the third IPL procedure.

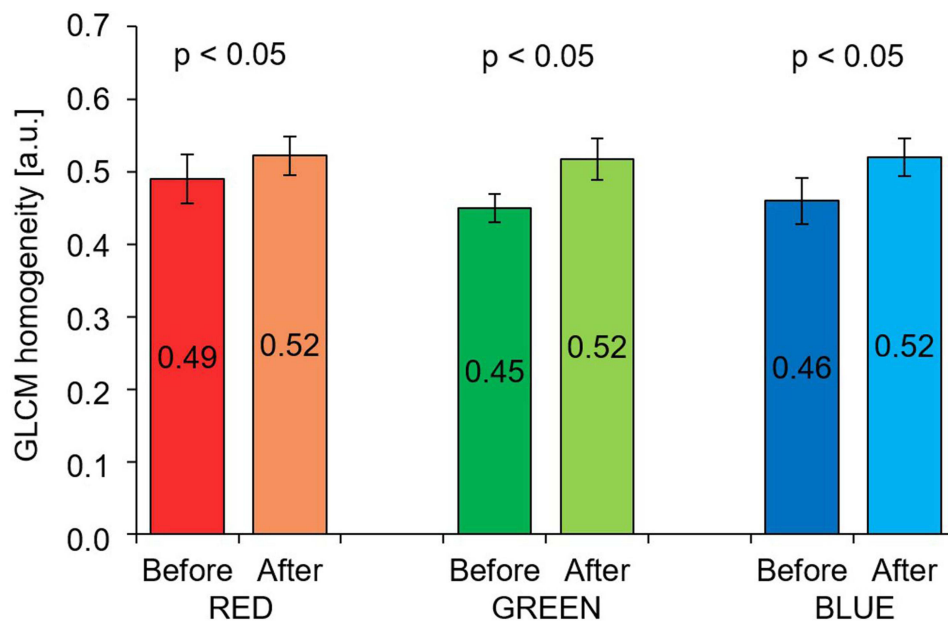


Figure 5 Mean GLCM homogeneity for RGB images of ROIs for the red, green and blue channels for all study participants before the first procedure and after the third IPL procedure.

predisposed to the occurrence of vascular lesions. The GLCM homogeneity analysis indicates that in the range of 3 tested channels, the red channel is the most homogeneous (0.49). The green and blue channels indicate that the image is less uniform for them.

Image Brightness Analysis

In order to quantify vascular lesions within the facial skin, a simple method for analysing the brightness of ROIs was also used. The mean, maximum and minimum brightness of images recorded in the RGB space was determined, and then they were converted to grey levels. It turned out that the analysis of brightness in the RGB space is not an effective measure of the severity of vascular lesions. There were no statistically significant differences in the brightness of images of vascular lesions before and after IPL procedures for any of the channels, despite a visually significant improvement. Thus, simple methods of analysing images, based on their brightness, do not allow for a quantitative assessment of vascular skin lesions.

Quadratic Tree Decomposition

An additional analysis based on quadratic tree decomposition was proposed to assess the distribution of vascular lesions. [Figure 6](#) shows a graphical interpretation of the results obtained from quadratic tree decomposition for the ROIs of subject No. 2.

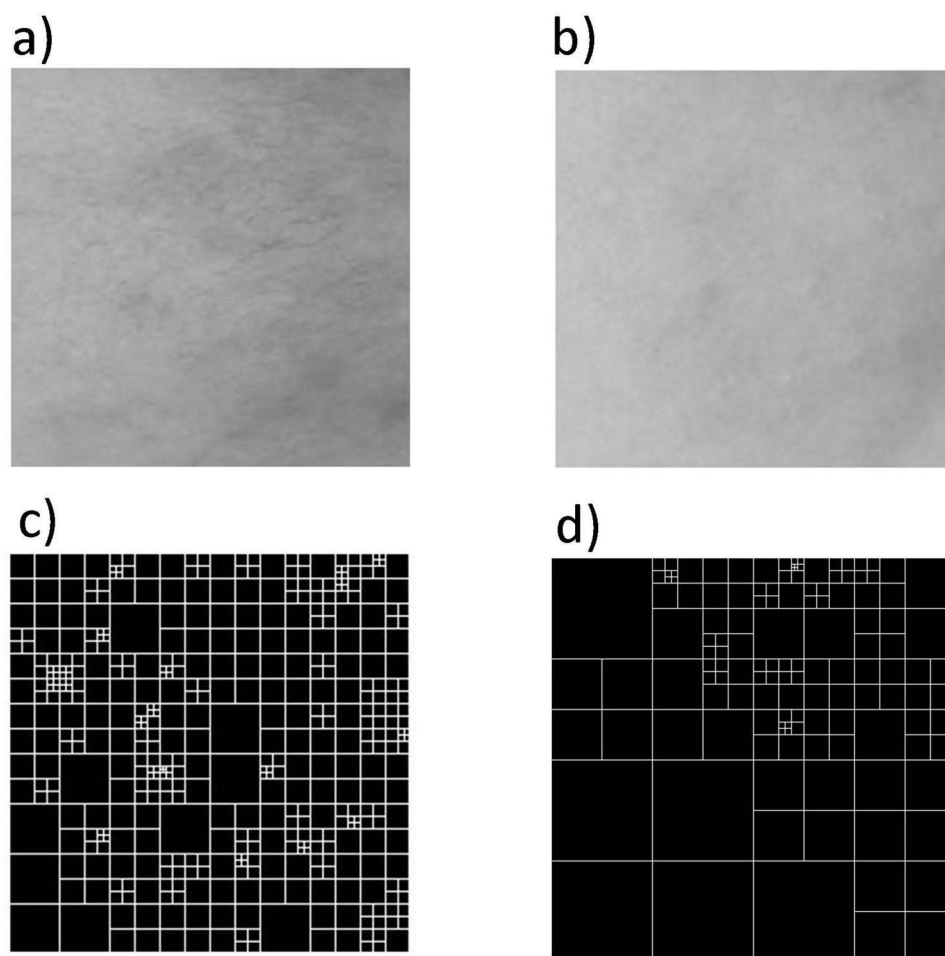


Figure 6 ROIs before (a) and after IPL procedures (b) for subject No. 2 and the graphical interpretation of the quadratic tree decomposition results before (c) and after IPL procedures (d), respectively.

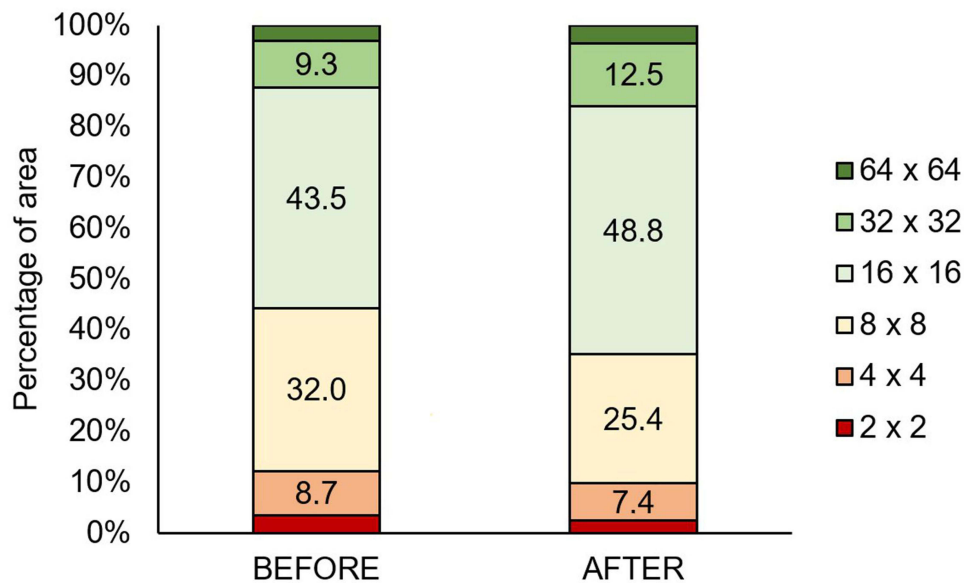


Figure 7 Percentage of squares with sides of 2×2, 4×4, 8×8, 16×16, 32×32 and 64×64 pixels resulting from the square tree decomposition of the ROI image for all tested subjects before and after IPL procedures.

The analysis of the figures, in quantitative terms, is as follows: the more squares with longer sides, the more homogeneous the image. The side length was related to the resolution of the camera used to acquire the images. The value of 12 was arbitrarily set as the threshold for the brightness difference between subsequent iterations of the quadratic tree decomposition division. The decomposition was performed in MATLAB R2010b using the standard homogeneity criterion ($\max - \min > 12$), equivalent to the rule implemented in MATLAB's `qtdecomp` for 8-bit images. This procedure yielded tiles of 2×2, 4×4, 8×8, 16×16, 32×32, and 64×64 pixels, with descriptors defined as counts and percentage contributions of each tile size. Size-specific block data can be retrieved with `qtgetblk` and visualized with `qtsetblk`. Paired before–after comparisons were performed using the Wilcoxon signed-rank test. We did not compute additional quadtree-derived features (such as area-weighted leaf size or boundary length), limiting outcomes to the tile-size distribution and its pre-/post-change under IPL. This produced a series of images (Figure 6) that were divided into squares with side lengths: 2×2 pixels, 4×4 pixels, 8×8 pixels, 16×16 pixels, 32×32 pixels, and 64×64 pixels. For an arbitrarily defined brightness threshold of 12, there were no areas (squares) with a side length larger than 64 pixels in the ROI images for all study participants. Figure 7 presents a quantitative analysis of the occurrence of areas with the above-defined sizes in the ROI for all tested subjects before and after IPL procedures.

Table 2 and Figure 7 present a quantitative analysis of the occurrence of squares with the above-defined sizes in the analysis area, ie ROI, for all tested subjects before and after IPL procedures.

The square size distribution after tree-square decomposition indicates that significantly more areas with inhomogeneous brightness can be identified for the skin ROI before IPL procedures. The number of smallest squares (2×2 pixels,

Table 2 Mean Number of Squares with Sides of 2×2 Pixels, 4×4 Pixels, 8×8 Pixels, 16×16 Pixels, 32×32 Pixels and 64×64 Pixels Resulting from the Quadratic Tree Decomposition of the ROI Image for All Subjects Before a Series of Treatments (Before) and After a Series of IPL Procedures (After)

	2×2		4×4		8×8		16×16		32×32		64×64	
	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
X	12.9	9.4	25.6	21.8	9.4	7.5	127.9	143.5	27.35	36.8	6.2	7.9
P	<0.05		<0.05		<0.05		<0.05		<0.05		<0.05	

Notes: x = mean, p = level of statistical significance.

4×4 pixels and 8×8 pixels) statistically significantly decreased after IPL therapy compared to the state before IPL procedures (Table 2 and Figure 7). Much more homogeneous skin colour (in terms of image brightness in RGB space) was revealed in the ROIs after IPL procedures. The analysis of the mean number of squares with sides of 16×16 pixels, 32×32 pixels and 64×64 pixels indicates that after IPL therapy the number of these squares increases statistically significantly. Thus, the proposed analysis method indicates that IPL therapy significantly increases skin homogeneity.

Discussion

Bearing in mind the above-mentioned limitations and methods for assessing vascular lesions known from the literature, new techniques for quantitative, objective analysis of vascular lesions before and after a series of IPL procedures have been proposed. The ideal method for quantitative assessment of skin lesions, including vascular ones, should be:

- a) Accurate, allowing for quantitative determination of the size, shape, colour and other features of skin lesions,
- b) Repeatable - measurement performed several times should provide the same results (within the measurement error),
- c) Sensitive, allowing for the assessment of the dynamics of lesions, eg in the context of the effectiveness of aesthetic medicine procedures,
- d) Specific, targeted at a given type of lesions, eg the appearance of melanotic lesions should not affect vascular lesions,
- e) Standardized – different clinical centres should be able to compare results,
- f) Independent of the operator - the method should minimize the operator's influence on the obtained results,
- g) Fast and efficient - this is of great importance in clinical practice when a specialist has very limited time for data acquisition and analysis,
- h) Non-invasive so that it can be safely used repeatedly, even on delicate skin areas - it should minimize patient discomfort,
- i) Easy to interpret, offering clear indicators or results that can be directly used in diagnosis or assessment of treatment effectiveness,
- j) Technologically available (cheap) – this is a sine qua non condition for implementation in various medical facilities,
- k) Clinically validated, supported by clinical studies that confirm its reliability and usefulness in the diagnosis and assessment of treatment of vascular lesions.

The analysis of the obtained results indicates that the proposed image analysis and processing algorithms meet the vast majority, if not all, of the above-mentioned criteria.

In the conducted research, the photos of participants were taken using the Fotomedicus system from Elfo (Poland), which allows for the acquisition of photos in cross-polarized and non-polarized light. As a technique based on the acquisition of photos in visible light (photography), it is cheap and easily available. Owing to the use of cross-polarization, it is possible to record photos without any reflections and other aberrations resulting from, for example, the presence of sebum and sweat on the skin, which strongly reflect visible radiation - so it is sensitive and repeatable. Moreover, polarized radiation, thanks to its characteristic spectral profile, can penetrate the skin slightly deeper than non-polarized radiation, which allows for more effective mapping of anatomical structures located below the epidermis.

The recorded photos were then processed and analysed using dedicated algorithms, including the GLCM algorithm. It allows for the quantitative identification of pixels that differ in terms of contrast (brightness). Two GLCM parameters were determined: contrast and homogeneity. The GLCM contrast analysis indicates a statistically significant reduction in GLCM contrast of the ROI after a series of treatments: from 7.1 to 6.5. It should be noted that although the GLCM algorithm is not derived from any physiological parameters of the skin, it works well when it comes to assessing the severity of vascular lesions. Vascular lesions are particularly troublesome when they are most visible. In turn, the visibility of skin lesions is the result of two factors: the number of lesions per unit of skin surface and the contrast between the lesion and unchanged skin. GLCM contrast indicates - in quantitative terms - what the mean contrast is

between pixels in the analysed area. The lower the contrast, the less visible the lesion is. The decrease in GLCM contrast after a series of IPL procedures confirms the clinical observations that IPL therapy is highly effective. The other analysed GLCM parameter is homogeneity. In this case, homogeneity can be related to the second important factor influencing the visibility of vascular lesions, ie the background. The analysis of GLCM homogeneity indicates an increase in this parameter after a series of IPL procedures, which also confirms that the image analysis and processing algorithm used for the quantitative assessment of vascular lesions has been chosen accurately.

The GLCM analysis applied in our study is an increasingly used tool in the evaluation of skin features captured in medical images. Wei et al¹⁶ demonstrated in their work the usefulness of GLCM analysis for identifying skin diseases such as herpes, dermatitis, and psoriasis. Fernandez et al¹⁷ proposed in their studies the extraction of features appearing on lesion images and their processing using the Gray-Level Co-occurrence Matrix (GLCM) method. In the detection phase, a set of classifiers determined the presence of malignant tumors. In the cited study, the accuracy of skin cancer detection exceeded 88.00%. In the research by Almeida et al¹⁸ the considerable usefulness of GLCM analysis in the evaluation of medical images of skin lesions was demonstrated. The investigators noted that GLCM analysis can be a useful tool in differentiating benign nevi from melanoma. Statistical methods using GLCM features, combined with red, green, and blue color information, applied to the analysis of human tissue microtexture and image classification for tumor detection, showed very high effectiveness at the level of 95% to 97%. In the study by Ansari et al¹⁹ the GLCM system was used to select specific areas on dermatoscopic images of skin lesions, which were then used to build a classifier. The classification determined whether the image represented cancerous or non-cancerous tissue. The accuracy of the proposed method was 95.00%. In the research by Odrzywołek et al²⁰ the effectiveness of chemical peels in acne therapy was assessed using GLCM analysis. Measurements of skin textural features were performed before, during, and after treatment. A significant increase in skin homogeneity and a decrease in contrast were observed during therapy, which correlated with a reduction in the number of acne lesions assessed by experts. GLCM proved to be an effective, quantitative tool supporting the subjective evaluation of dermatologists. Pang et al²¹ demonstrated the high usefulness of GLCM analysis for evaluating the effects of cosmetics and cosmetology procedures on skin texture, understood as the spatial distribution of regular and interdependent gray levels of pixels within an image area. In the study by Wawrzyk-Bochenek et al, GLCM analysis was successfully used to assess the degree of hyperpigmentation reduction after microneedle mesotherapy with vitamin C.¹³ In other studies, the authors demonstrated the effectiveness of kojic acid therapy for hyperpigmentation, analyzing changes in GLCM contrast and homogeneity.²² After treatment, a decrease in GLCM contrast was observed in about 83% of cases, and an increase in skin homogeneity in about 67%.

In the present study, we did not limit ourselves solely to GLCM analysis. The next stage of the research was the use of the quadratic tree decomposition algorithm. This algorithm divides the image into two parts and verifies whether the mean brightness in both parts of the image is equal to or greater than a given threshold. The performed analysis indicates the usefulness of the QTDCOMP algorithm for quantitative assessment of vascular lesions in response to IPL procedures. A series of high-energy light treatments reduces the number of small squares, ie 2×2 , 4×4 and 8×8 pixels, and increases the number of squares with longer sides, ie 16×16 , 32×32 and 64×64 pixels. The image of vascular lesions is therefore consistent with clinical data and becomes more homogeneous after a series of treatments (the lesions are less visible). It should therefore be noted that although the QTDCOMP algorithm works based on brightness analysis, which turned out to be a useless tool in assessing the severity of lesions, the brightness parameter used in the proposed algorithm can be a quantitative measure of the severity of vascular lesions.

Therefore, it can be assumed that the applied GLCM (Gray-Level Co-occurrence Matrix) and QTDCOMP (Quad-Tree Decomposition) algorithms meet a number of important requirements that a quantitative method for assessing skin lesions should fulfil. Accuracy: GLCM and QTDCOMP algorithms quantify size, shape, colour and other features of skin lesions, such as contrast and homogeneity. As a result, it is possible to precisely determine the severity of erythema and the dynamics of lesions after IPL therapy. The accuracy was illustrated by statistically significant differences in results before and after a series of treatments.

Repeatability: Studies have shown that the algorithms used provide repeatable results, which is crucial for their reliability. Image analysis methods such as quadratic tree decomposition provide consistent results across multiple measurements.

Sensitivity: The algorithms are sensitive enough to detect subtle changes in the structure of the skin and blood vessels before and after IPL therapy, which allows for the assessment of the effectiveness of aesthetic medicine treatments. Changes in parameters such as GLCM contrast and GLCM homogeneity after treatments indicate the sensitivity of these methods to skin lesions.

Specificity: These methods are focused on the analysis of vascular lesions and erythema, which minimizes the impact of other skin lesions such as melanotic ones. The research focused on assessments specific to vascular problems of the skin, which confirms the specificity of the algorithms.

Standardization: The study indicates the use of a standardized image acquisition system (Fotomedicus), which enables comparison of results between different clinical centres. This is crucial for standardizing the method and enabling its wide application.

Independence from the operator: The algorithms minimize the impact of operator's subjective judgments, which is important in achieving objective results. The image acquisition and analysis process has been designed in a way that reduces the possibility of human errors.

Speed and efficiency: The algorithms are designed to be efficient and fast in clinical practice. The examples presented in the paper show that analyses can be performed in real time, which is important in everyday clinical work. Image acquisition from one patient takes a trained operator less than 3 minutes. The algorithm running time is less than 1 second for a standard computer.

Non-invasiveness: Methods of acquiring images in visible light are completely non-invasive, which allows them to be used repeatedly, even on delicate skin areas, without causing any patient discomfort.

Ease of interpretation: Results obtained with the GLCM and QTDCOMP algorithms are easy for clinicians to interpret. Indicators such as GLCM contrast and homogeneity provide clear and understandable information that can be used in diagnosis or treatment evaluation.

Technological availability: Technologies used, such as the Fotomedicus system or other skin image acquisition systems, are available on the market and relatively cheap, which allows for their implementation in various medical facilities.

Clinical validation: The paper presents results obtained from a group of 38 subjects, which indicates clinical validation. Statistically significant results confirm the reliability and usefulness of the methods in the diagnosis and assessment of treatment of vascular lesions.

To sum up, the proposed image analysis and processing methods based on advanced, dedicated algorithms such as GLCM and QTDCOMP can be an effective method for quantitative analysis of skin lesions. The proposed methods may be used in the optimization of therapeutic procedures and active substances used in the treatment of vascular lesions. In the future, they may also constitute an interesting starting point for correlating the effectiveness of therapy with the initial characteristics of the skin, including the condition of skin blood vessels.

Apart from the proposed methods of objective evaluation of erythema and vascular lesion reduction, the literature also reports the use of narrow-band reflectance spectrophotometry, hyperspectral imaging, and computer-based image analysis tools.^{23–25} Tao et al²³ described the use of VISIA system photographs in the “red area” mode together with ImageJ software for the quantitative assessment of erythema in patients with rosacea. The objective indices obtained – redness intensity and the percentage of the area affected by erythema – showed significant correlation with validated clinical scales such as the grading system for rosacea (SGS), clinician erythema assessment (CEA), patient's self-assessment (PSA), and investigator's global assessment (IGA). The authors demonstrated that this method enables an objective and precise evaluation of both the severity and the extent of erythema on the patient's face, facilitating monitoring of therapeutic outcomes. Narrow-band reflectance spectrophotometry is considered a sensitive, repeatable, and specific method for objective measurement of skin colour. In the study by Hexsel et al²⁴ this tool was successfully applied both to assess the reduction of pigmentation and to evaluate erythema severity during melasma therapy. Abdlaty et al¹² reviewed techniques for objective erythema assessment, including diffuse reflectance spectroscopy, photometry, hyperspectral imaging, and computer-based image analysis tools. The authors emphasized that instrumental methods ensure higher repeatability and precision compared to subjective clinical assessments.

In earlier studies, the authors of this manuscript demonstrated the applicability of hyperspectral imaging as a method for assessing the effectiveness of erythema reduction.²⁵ The most effective evaluation of vascular changes using hyperspectral

imaging was obtained at wavelengths of 420 nm and 580 nm. They also indicated the usefulness of hemispheric directional reflectance in the assessment of erythema and vascular lesion reduction.

Limitations of this study should be acknowledged. First, there was no control group (eg, sham treatment or untreated area), which reduces the certainty that all observed changes were due solely to IPL. Second, although images were coded, potential lack of full blinding in analysis cannot be entirely excluded. Third, the global normalization approach applied to all images may have influenced relative contrast values. Fourth, the threshold used in QTDCOMP¹² was arbitrarily chosen, which, while practical, may limit reproducibility across different imaging conditions. Fifth, the analysis relied primarily on the green channel as a model for erythema, which is a simplification and may not fully capture the complexity of vascular changes in different skin types. Sixth, the lack of long-term follow-up means that durability of the observed improvements cannot be assessed. Moreover, we did not include correlation with standardized clinical grading or subjective assessment, which could further validate the objective metrics. Finally, as a single-center methodological pilot, the generalizability of our findings may be limited and requires confirmation in larger controlled studies. Furthermore, absolute color scales or lesion-intensity annotations were not included, because all images were globally normalized and not photometrically calibrated. Under this preprocessing, absolute gray-level values are not radiometrically meaningful, and apparent Δ -intensity would partly reflect normalization rather than true optical fading. Our acquisition was not calibrated with a reflectance standard, so quantitative scales could misleadingly suggest comparability across different skin phototypes or sessions. Adding per-panel intensity annotations could therefore have led to over-interpretation of non-endpoints. Instead, the prespecified endpoints—GLCM contrast/homogeneity and QTDCOMP tile-size distributions—were chosen to capture spatial pattern changes and were sensitive to treatment effects even when mean brightness showed no significant shift. While these limitations affect the strength of conclusions regarding IPL efficacy, the primary focus of the study was to validate the utility of GLCM and QTDCOMP as objective methods for image-based assessment of vascular lesions.

Conclusion

The research on the response of vascular lesions to high-energy IPL, using clinical photography techniques supported by dedicated image analysis and processing algorithms, allowed several important conclusions to be drawn. Registration of images in cross-polarized light effectively visualized facial vascular lesions, while a series of three IPL procedures can achieve a clinically satisfactory reduction of such changes. GLCM provided reliable identification of vascular skin lesions, confirming its value as a texture-based quantitative measure. In contrast, simple image analysis methods, such as brightness evaluation, were not suitable for quantitative identification of vascular features. Overall, the proposed quantitative analysis methods offer significant advantages over currently used qualitative or semi-quantitative approaches: they rely on objective numerical values, eliminate subjectivity, improve reliability and repeatability of results, and facilitate comparisons both within and across studies.

Abbreviations

GLCM, Gray-Level Co-occurrence Matrix; IPL, intense pulsed light; QTDCOMP, Quadratic Tree Decomposition; RGB, red, green, blue; ROI, region of interest; UV, ultraviolet.

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Disclosure

The authors report no conflicts of interest in this work.

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