A novel instrument aimed at measuring hypertrophic scar formation

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Hypertrophic scaring is a condition that can occur after thermal trauma and can lead to loss of function and psycho-social complications. Assessment of the development of a hypertrophic scar currently relies on visual inspection and grading. In this paper we propose a system based on polarized illumination and collection capable of capturing images of scars and quantify their roughness. Models of rough surface roughness are ultimately used to quantify the level of roughness of scarred skin compared to normal skin.

1. Introduction
Hypertrophic scarring is still a poorly understood and devastating morbidity following injury, particularly thermal trauma with prevalence reported as high as 67% [1]. Scar contractures can lead to significant reduction in function and inhibit patients from returning to work, participating in leisure activities and even render them unable to provide care for themselves. In addition these patients suffer great psycho-social setbacks due to their disfigured appearance [2]. There is a continued need for better assessment techniques to diagnose and treat patients with scar. This is underscored by the fact that greater than 30% of the respondents to an American Burn Association Rehabilitation committee’s survey on research needs in burn care indicate that scar management should be a priority [3].
Fig. 1 Examples of patients with hypertrophic scar from burn injury. Arrows denote large high-tension scar bands that are inhibiting neck movement. Asterisks indicate areas with raised scar.

The assessment of scar is limited by the lack of accurate objective measurement tools. The Vancouver Scar Scale (VSS), currently the accepted clinical scar assessment tool, was introduced [4, 5] in the nineties and relies on the physician subjective evaluation of skin pliability, height, vascularity, and pigmentation, in a rating of 0 to 4. Recently several groups have proposed improvements to the scale, both with more pertinent metrics [6, 7], as well as the introduction of novel instrumentation [8, 9, 10, 11, 12].

Further work is needed in a controlled model to assess the natural history of scar. The research effort described here proposes a new instrument aimed at obtaining quantitative parameters of hypertrophic scar formation based on skin roughness and optical properties.

2. Theory

Polarimetric techniques are extremely sensitive to roughness [13]. Assessment of skin roughness including wrinkles has been successfully performed on skin using spectro-polarimetric techniques [14, 15]. Jacques et al. used polarized light imaging to determine the margins of certain skin cancers relying on the contrast provided by a cancer induced disruption of the underlying collagen matrix [16, 17]. Jacques et al. also showed examples of scar tissue exhibiting lower degree of polarization compared to normal tissue possibly due to randomized collagen restructuring [18].

Studies on rough surface scattering [14] on non-biological samples have shown that polarized light can be used to discriminate different scattering mechanisms. The rough-surface-scattering component can be highlighted by changing the direction of the light source, as well as the polarization of the illuminator and collector. Figure 1 shows the geometry for out-of-plane measurements, where $\theta_i$ is the incident polar angle, $\theta_s$ is the scattering polar angle, and $\phi$ is the azimuth, or out-of-plane, angle.

Fig. 2 Out of plane geometry and nomenclature

For a given scattering geometry, we measure the Stokes vector intensity $S$ of the back-reflected light, modulating the detector polarizing elements. The Stokes vector can be divided into its polarized $I_{pol}$ and unpolarized components $I_{unpol}$. 
We also characterize the polarization in terms of the principal angle of the polarization ellipse, 
\[ \eta = \arctangent(S_2/S_1)/2 \]. All these parameters are exquisitely sensitive to rough surface scattering as shown below.

We simulate the effect of different surface roughness on the polarized portion of the remitted beam for different incident angles using the MIST program [19]. Shown in Fig. 3 is the result as the root mean square slope (RMS) of a skin sample is allowed to change between 0 and 1 in steps of 0.2 (RMS slope for skin has been found to lie between 0.2 and 0.4 [20]. The deviation from the normal (Fig.3 on the right) will have a strong polarized signature.

\[
S = \begin{bmatrix} S_0 & S_1 & S_2 & S_3 \end{bmatrix}^T = I_{\text{upol}} \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} + I_{\text{pol}} \begin{bmatrix} 1 & S_0/S_{\text{pol}} & S_2/S_{\text{pol}} & S_3/S_{\text{pol}} \end{bmatrix}^T
\]

\[
S_{\text{pol}} = (S_1^2 + S_2^2 + S_3^2)^{1/2}
\]

Fig. 3 The polarized portion of the remitted beam \( P \) (Eq.2) as the RMS slope varies between 0 and 1. Clear changes in polarized signature are visible. On the right hand side the sum of the polarized response at every angle (S) divided by the initial the polarized response (S0).

3. Material and Methods
In previous studies we developed a polarimetric system with no moving parts that acquires Stokes vector images as functions of illumination direction, hence allowing for the calculation of the previously described parameters [14]. The system consists of sixteen illumination tubes directed towards a sample position. Each illumination tube, has a tri-color light emitting diode (LED), a polarizer, and a lens and provides collimated and linearly polarized light centered at wavelengths of 472 nm, 525 nm, and 633 nm. Each polarizer is aligned so that the incident illumination is linearly polarized with its electric field 45° from the plane of incidence. One illuminator has a polar angle of \( \theta_i = 0° \), six have a polar angle \( \theta_i = 24° \), and nine have a polar angle \( \theta_i = 49° \). The system was modified to include a 12-bit digital charge-coupled device (CCD) capable of up to 60 frames per second acquisition. The camera views the sample with a polar angle of \( \theta = 49° \). Two liquid crystal variable retarders (LC1 and LC2) followed by a polarizer (POL) modulate the scattered light before reaching the camera. The rotation of the retarders and the polarizer remain fixed, while the retardances are chosen to span the Poincaré sphere and enable Stokes vector measurements.

The system was calibrated with a well-characterized rough gold standard; a facet model was able to describe the modulation of \( \eta \) with an error << 1%.
4. Results

Images of a foot thermal scar of a 26 years old volunteer were obtained with the current system all illumination angles where used and the Stokes vector calculated for each position. From the Stokes vector we calculated the degree of linear polarization (PLin) the degree of circular polarization (PCirc) the polarized and unpolarized portion of the remitted light (S0Pol and S0unpol respectively) and the principle angle of polarization $\eta$ for each pixel in the images. Figures 5 and 6 show two such sets for different incident angles. As shown below the roughness of the scar stands out compared to the normal skin background, and the polarized response is strongly influenced by the illumination angle.
Fig. 5 Images obtained for an azimuth angle $\phi = 180$ degrees

Fig. 6 Images obtained for an azimuth angle $\phi = 36$ degrees
Fig. 7 Principle angle of polarization for different incident illumination azimuthal angles, $\theta = 24$ degrees.

Finally a region of interest of (100 pixels x 100 pixels) was selected on the visible portion of the scar, the resulting principle angle of polarization was plotted versus the incident angle, Fig. 7 (black crosses) symbols. A facet model was used to simulate the polarized behaviour of the scar (solid line). The same process was repeated for a portion of the intact skin (red filled symbols). A clear difference in polarized remittance can be seen.

Conclusions

The characterization of hypertrophic scars is currently conducted with visual inspection. New tools mostly based on spectral remittance are becoming more common. We have introduced an imaging system aimed at characterizing scars using their roughness. The advantage of this technique is in its sensitivity, so that not only rough scarred skin can be measured but also normal skin, (less rough). The technique has also the advantage of producing quantifiable metrics hence allowing for more effective studies on scar treatment and reduction.

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