

# Polarized light imaging with a hand-held camera

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## ABSTRACT

Polarized light imaging can facilitate clinical mapping of skin cancer margins and can potentially guide clinical excision. A real-time hand-held polarized-light system was built to image skin lesions in the clinic.

The system consisted of two 8-bit CCD cameras (Camera 1 and Camera 2) mounted on two sides of a polarizing beam-splitter. A polarized light source was mounted on the camera assembly and illuminated the patient's skin. Light was polarized parallel to the source-patient-camera plane. The light, reflected from the patient, was collected with an objective lens mounted on the beam splitter and divided into a horizontal (H) and vertical (V) component. The H component was collected by Camera 1, and the V component was collected by Camera 2. A new image was generated based on the polarization ratio  $(H - V)/(H + V)$  and displayed. This image was sensitive to the superficial skin layer and some early clinical examples are presented.

A web version of this paper is available at the following web site: [optics.sgu.ru/SFM/2002/internet/Jessica/](http://optics.sgu.ru/SFM/2002/internet/Jessica/).

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## 1. INTRODUCTION

The polarization status of a beam of light propagating through light-scattering media such as biological tissues, micro sphere solutions, or an atmosphere with particulate, can be altered either by scattering events or by birefringent properties of the media<sup>1</sup>. So a light beam traveling through the superficial layers of the skin will have its polarization status changed by the local birefringent matrix of collagen fibers. Since skin cancer often arises in the dermis where it disrupts the natural order of the collagen matrix, polarized light imaging can be used to detect cancer.

A schematic of a prototype polarization camera is shown below in Figure 1.

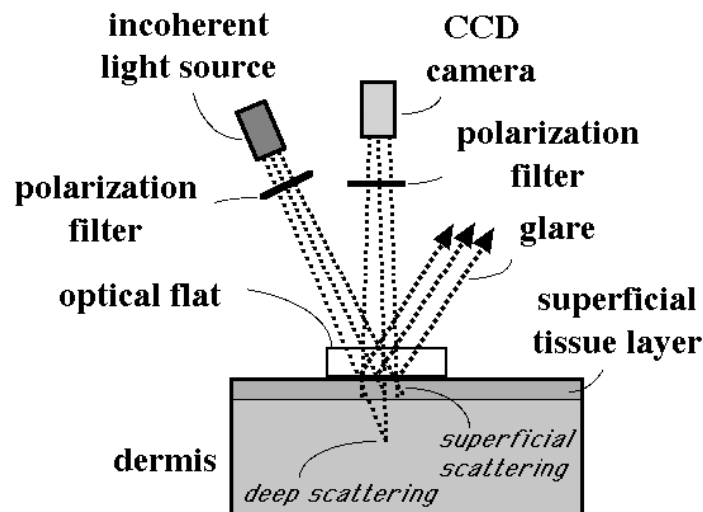


Figure 1: Set up of the polarized camera

The incident light is linearly polarized parallel to the scattering plane (the source-tissue-camera plane). An optical flat enforces a uniform skin/glass interface and reflects glare away from the camera.

The polarized scattered light and the diffusely randomly polarized scattered light reach the camera after passing through a linear polarizer that can be oriented parallel (Horizontal) or perpendicular (Vertical) to the scattering plane.

Polarization Mathematics:

After the images, Horizontal and Vertical, are acquired they are algebraically combined to yield a “Polarization Image” using equation 1.1:

$$\text{Polarization Image} = \frac{H - V}{H + V} \quad (1.1)$$

The melanin pigmentation acts as a neutral density filter and attenuates both the superficial and deeply penetrating light equally. If  $t_m$  is the attenuation due to this layer then the polarization image may be decomposed into its fundamental components as shown in equation 1.2:

$$\text{Polarization Image} = \frac{s \times t_m \times (H_{\text{superficial}} + H_{\text{deep}}) - s \times t_m \times V_{\text{deep}}}{s \times t_m \times (H_{\text{superficial}} + H_{\text{deep}}) + s \times t_m \times V_{\text{deep}}} \quad (1.2)$$

Where  $s$  is the light source distribution. This equation shows how by normalizing by  $(H+V)$ , we can completely cancel the effect of the source and superficial pigmentation. The polarization of the light reaching the deep layers of the skin is completely randomized, and when back scattered into the camera its effect is equally distributed in the Horizontal and Vertical images. The light is cancelled in the numerator, and the resulting image is given by equation 1.3:

$$\text{Polarization Image} = \frac{H_{\text{superficial}}}{H_{\text{superficial}} + H_{\text{deep}} + V_{\text{deep}}} \quad (1.3)$$

This equation shows how the polarization image is sensitive to superficially back scattered light.

The first prototype of the polarized light camera was built using a 16-bit CCD camera (Roper Scientific, NJ, USA), two polarizers (Coherent Ealing Electro Optics Ltd., Watford, England) and a Xenon lamp (Oriel, Stratford, CT). The polarizers were rotated by hand to collect the H and V images using IPLab imaging software. The polarized image was reconstructed using Matlab.<sup>2</sup>

When used in the clinic the camera was attached to a balanced arm with a universal joint to allow for positioning on the patient's affected areas.

It was evident, after the initial clinical testing, that a much smaller device was preferred. In particular we decided to design a smaller and completely automatic camera that could display the polarized image results in real time.

The new hand-held polarized camera was designed using a polarizing beam splitter cube, two CCD cameras, and one objective lens.

The polarizing beam splitter cube split the image into its Horizontal and Vertical polarized components. Two images could be collected simultaneously: Camera 1 collected the Horizontal image and Camera 2 collected the Vertical image. The polarized image given by equation 1.1 was calculated programmatically.

## 2. MATERIALS AND METHODS

The hand-held prototype of the polarized camera is shown in Figure 2. The spherical casing, used to protect the inner parts, was chosen for its ergonomic characteristics. The sphere diameter was 10 cm, small and light enough to feel comfortable in a user's hand. The polarized light source was constructed with three ultra bright white LED mounted on an acrylic support. The LEDs were battery powered by three AA batteries that were stored in a compartment in the

bottom of the sphere. LED light was polarized parallel to the source, sample, and detector plane with a sheet polarizer. The light source assembly was oriented at an angle  $\sim 30$  degree to the objective lens axis to avoid the glare coming back into the camera.

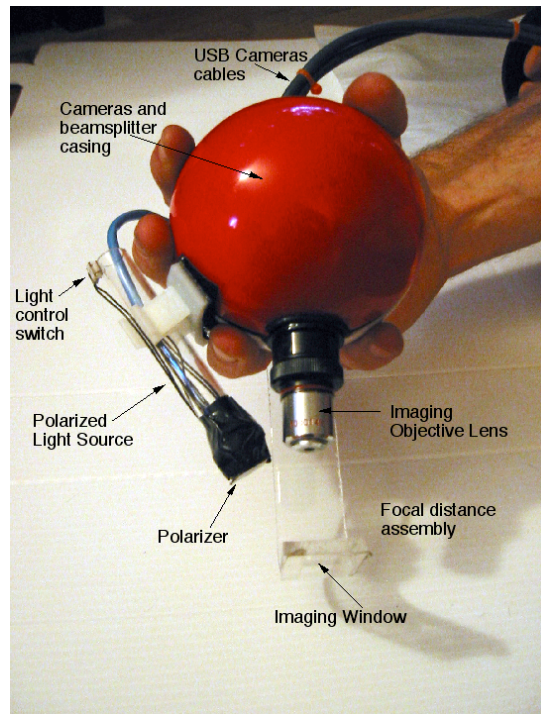


Figure 2: The clinical hand-held polarization system, spherical casing protects the main components: a polarizing beam-splitter cube and two web cameras.

A fixed distance between the imaging plane and the cameras was maintained using an acrylic support. The acrylic support was also used as a mount for a glass cover slip that was used as an optical flat. During camera operation the glass cover slip was in contact with the skin and a drop of water was used to achieve index matching

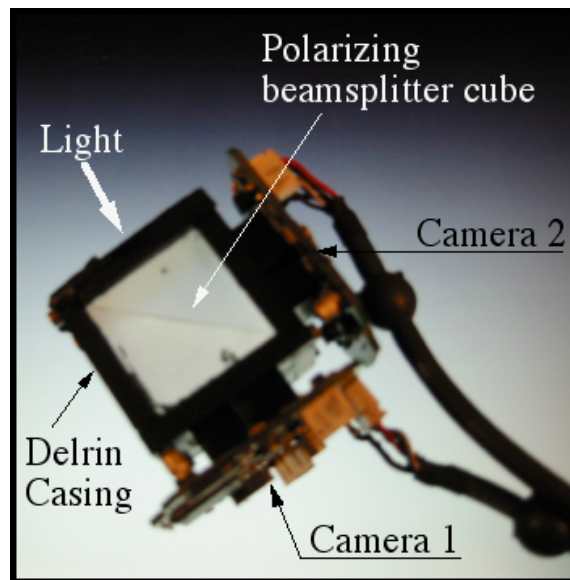


Figure 3: the inner components of a polarization camera are a polarizing beam-splitter cube, and 2 web-cameras.

An objective lens (PL 4/0.1) was used as the imaging lens, the field of view was approximately 5x5 mm.

The inner part of the hand-held polarization system is visible in Figure 3, it is composed of a broadband polarizing beam splitter cube (Melles Griot, Carlsbad, CA, USA) with 0.01 nominal extinction, two USB Quickcam Pro 3000 Web-Cameras (Logitech Inc., Fremont, CA, USA) and a custom made Delrin box that encased the beam splitter cube and supported the two cameras in fixed positions.

The polarization image was calculated by the software in real time and displayed on the screen (Right window), together with the Horizontal image (Left). Image size was 400 by 400 pixels. Maximum frame rate for this image size was 6.5 frames/sec. The frame rate could be improved decreasing the image size, using 250 x 250 pixels as the image increased the frame rate to 15 frames/sec.

The color CCD cameras collected images composed of Red, Green, and Blue images. These three images generated three polarized RGB images that could be displayed on the screen during collection. This provided crude spectroscopic information of skin lesions. The software allows the user to average multiple pictures before displaying the results on screen. This operation was implemented to limit small movement artifacts. Up to 20 images could be averaged.

## 2.1 Polarized system performance tests

The camera consists of a 1/4" color CCD (640x480 pixels), the CCD chip is mounted on a small, circa 4 by 3 cm, control board, which is an ideal size for a small portable package.

The original camera round case was removed, as well as the original imaging lens, to facilitate mounting the camera on the polarizing beam splitter cube. A few test were performed to assess the quality of the cameras and the polarizing optics.

2.1.1 Dark noise over time: this test was done to determine if camera dark noise increased over time. The test was performed with the camera software shutter off, and an acquisition time  $> 0$ . The test was performed in the dark, and images were captured at increasing time intervals. Camera streaming was interrupted only during image acquisition. The test was run for two hours, we expect to use the camera in patient observations for much shorter times. The captured images were processed using Matlab and results are shown in Figure 4. The process consisted in calculating the mean and standard deviation for all of the  $400 \times 400 = 16000$  image pixels, for the three (RGB) images. The B channel dark noise is noticeably higher than the R and G, but the general trend of noise is quite flat. The fact that the dark noise does not increase over time allows us to subtract it from the image programmatically.

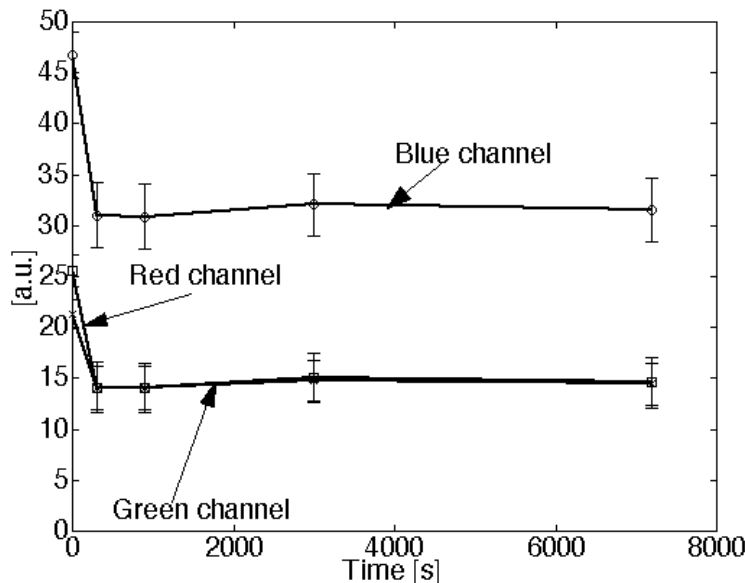


Figure 4: Test on the camera dark noise drift over time, the three curves show the mean and standard deviation of a dark image. The three curves represent the red, green and blue images.

2.1.2 Camera repeatability: this test was performed to establish the pixel count variation during multiple acquisitions. Our target was a checkerboard; two main regions are visible on the board dark/black squares and white/bright squares. A group of 20 images of the checkerboard was captured over a 10 minutes period. The variability from image to image was analyzed using Matlab. 20 different pixel locations were chosen on the images. For every pixel location the mean and standard deviation among the 20 images was calculated, and it is shown in Figure 5. The inset in the plot shows that the standard deviation from a pixel population average is less than 3 counts.

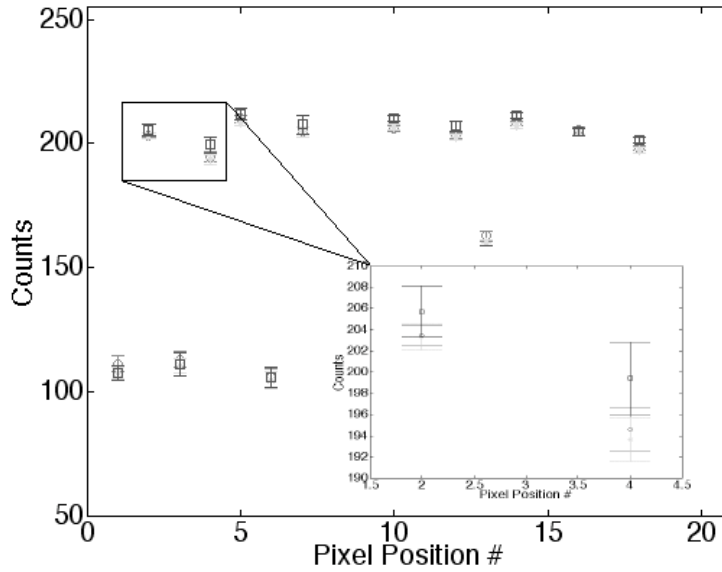


Figure 5: Test on web-cameras repeatability, the image-to-image variation was tested for 20 subsequent captured images, the variation, visible in the plot inset, was less than 3 counts.

Figure 6 shows histograms of all the collected points for all three channels. Three pixel values populations are visible: the black squares (~ 100 counts), the white squares (~ 200 counts), and the bordering lines between dark and white squares (~150 counts). This graph shows how the light variation across the imaging field was less than 20 counts. Concluding that our field of view is uniformly illuminated.

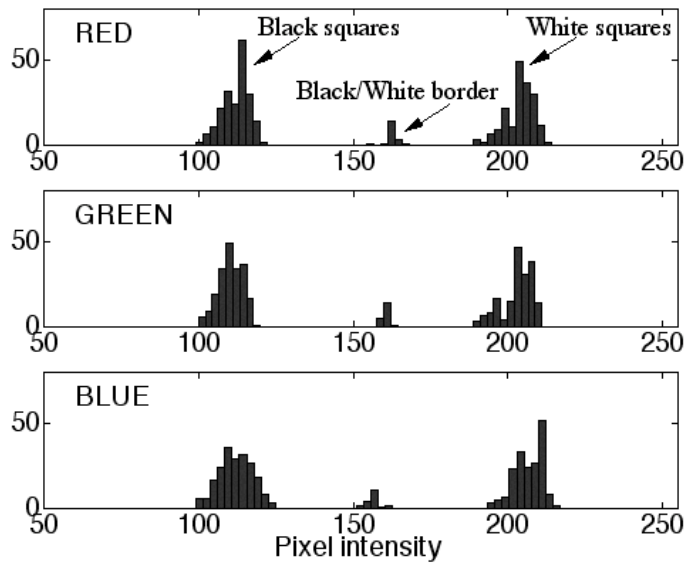


Figure 6: The polarized illumination varied across the field of view. The histograms above show three main areas on the imaged checkerboard. Points collected on black squares had pixel intensity around 100 counts, points collected on white squares were ~ 200 counts and bordering lines ~ 150 counts. For all three regions, the pixel variation was ~ 20 counts, this demonstrates that the illumination across the field of view was reasonably uniform.

2.1.3 Polarization optics tests: we tested the performance of all the polarizing elements in transmission mode. The light source was positioned in front of the hand-held camera. The sheet polarizer axis was aligned with the beam splitter horizontal axis. The orientation of the sheet polarizer axis was then increased in intervals of 20 degrees. At each angle two images were collected: one with Camera 1 (Horizontal) and one with Camera 2 (Vertical).

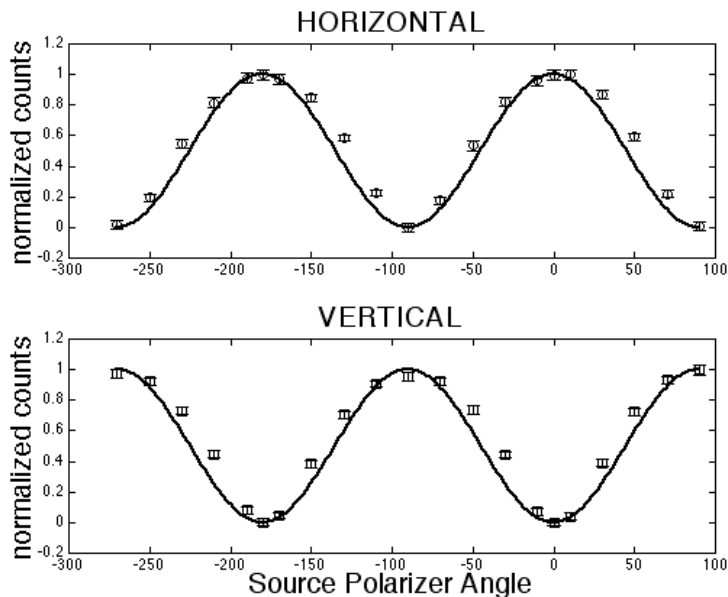


Figure 7: Analysis of polarizing optical component, Malus' law was reconstructed rotating the source polarizer 20 degrees at the time and capturing images with the horizontal and vertical camera. The plot show the mean and standard deviation of a Region Of Interest in the image. The chosen ROI was the central 100 x 100 pixels.

The transmitted light beam filled most of the camera's field of view. The pixel intensity counts of the central 100 x 100 pixels were selected to eliminate any beam shape artifact. Dark noise was subtracted from every image. Images were then normalized by the maximum transmittance image. The mean and standard deviation of the resulting values are plotted in Figure 7.

### 3. THE POLARIZING HAND-HELD CAMERA SOFTWARE

The hand-held polarized light camera controlling software was written in C. The software was developed using the QuickTime SDK (Software Development Kit)<sup>3,4</sup>. QT is a system-level code package on most computers that support multimedia tasks. When the code runs, it calls QT to create and show movies. The software was developed on a Macintosh platform.

#### 3.1 Software description:

1. Initialization
2. Generate a dialog box to establish file name in case of save
3. Create 2 windows, use the left window for the polarization image and the right window for the Horizontal image
4. Initialize Sequence Grabbers for camera 1 and 2
5. Generate a dialog Box for camera 1, let the user modify camera parameters as Gain, Shutter, window orientation.
  - a. For camera 2 the user needs to flip the window horizontal to correct for the beam splitter mirror effect.
6. Event Loop
  - a. If the s key is pressed: save currently displayed images in PICT format, without asking the user
  - b. If the 1 to 5 keys are pressed: average 1 to 5 images, if the 0 key is pressed average 20 images
  - c. If mouse click on left window: switch in between R,G,B channels.
  - d. If mouse click on right window: switch camera off.
  - e. If no key is pressed: work on current frames.
7. Decompress a sequence of frames
8. Get R,G,B values for every pixel for camera 1 and 2
9. Average frames if necessary
10. Reconstruct the polarized image calculating Pol for every pixel
11. If Pol is negative or equal to 0, set Pol to 0.0001
12. Copy pixel values for the Polarized and for Horizontal image back to window 1 and 2.
13. Return
14. END

### 4. RESULTS

We show here some preliminary images of skin features and lesions collected with the hand-held polarized camera. The image on the left is the polarized green image in grayscale. The green image was the most clear among the three acquired images, this is due to the CCD camera high sensitivity to green wavelengths. On the right hand-side we show the horizontally polarized image in gray-scale format, both image contrasts were enhanced using the Photoshop auto-balance feature.

Four different skin features are shown: a Tattoo, a Mole, a Freckle, and a Melanoma.

#### 4.1 A tattoo

Image of a tattoo is shown in Figure 8, the dark areas in the right Horizontally polarized image are the tattoo. In the polarized images the tattoo becomes white, while the surrounding areas are gray. This behavior is confirmed by similar tests using the 16-bit CCD camera. We believe that the ink particles, that constitute the tattoo, act as small mirrors, reflecting polarized light directly into the camera with the original status of polarization preserved. White corresponds to a degree of polarization = 1, fully maintained. The darker the image becomes the lower the degree of polarization.

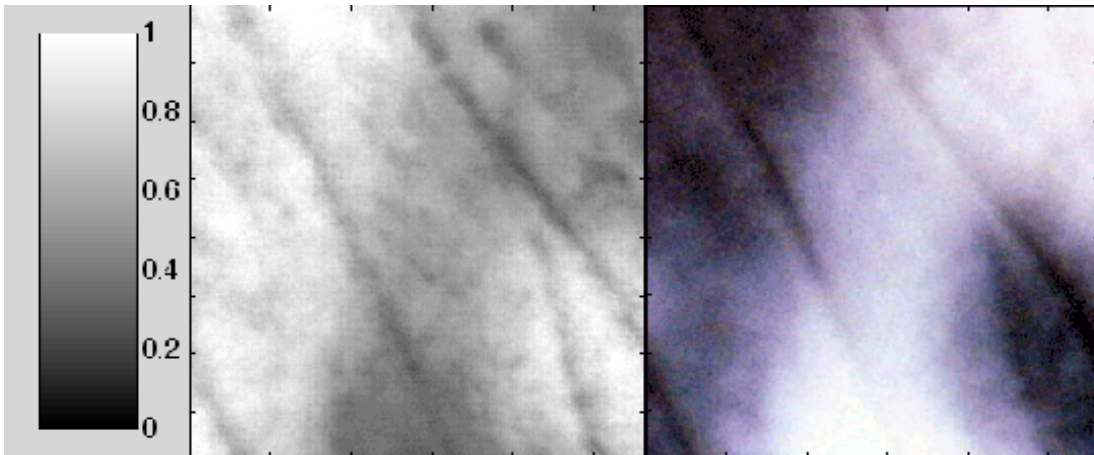


Figure 8: Image of a tattoo; on the left we show the polarized image on the right the Horizontal image.

#### 4.2 A mole

The polarized image enhances the superficial features of the skin. In the polarized image: wrinkles, air follicles, and the mole structure, are very clear, especially compared to the normal image on the right. In the polarized image, the mole appears white and has interesting three-dimensional features.

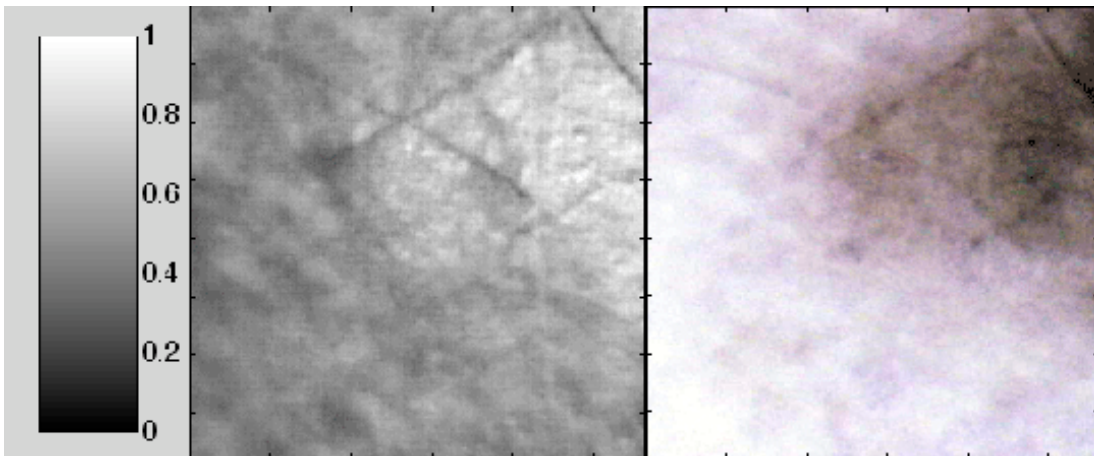


Figure 9: Image of a mole; on the left we show the polarized image on the right the Horizontal image.

#### 4.3 A freckle

A freckle disappears to the polarized camera. As described in equation 1.2, the melanosomes pigmentation effect visible in the normal image and is cancelled in the polarized image since it effects both the Horizontal and Vertical images.



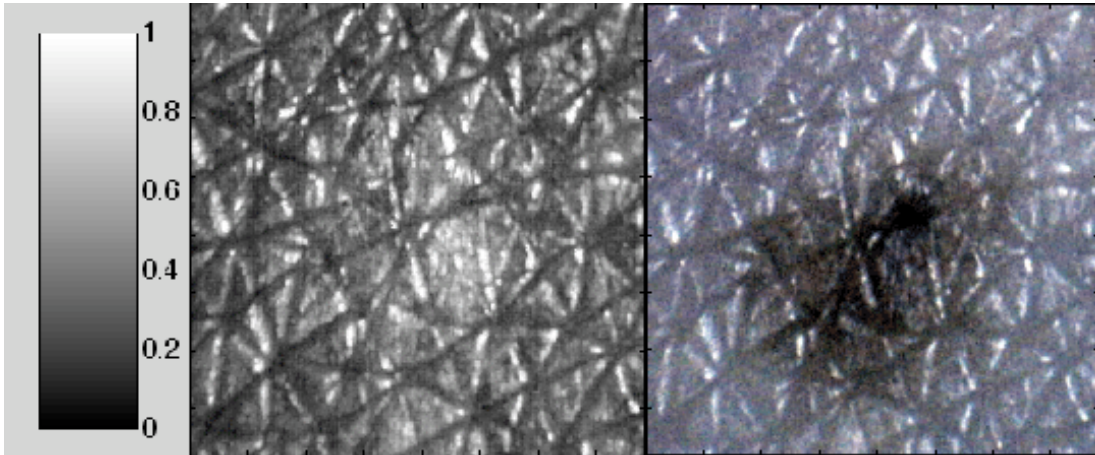


Figure 10: Image of a freckle; on the left we show the polarized image on the right the Horizontal image

#### 4.3 A melanoma.

The images of melanoma, Figure 11, 12, were collected at the Dermatology Department of the Oregon Health & Science University during a Mohs surgery procedure. The melanoma appears black / blue in the Horizontal image on the right and to the naked eye. In the polarized image on the left the melanoma appears white / gray, the branching of the melanoma in healthy tissue is very visible in this picture and in the one below. We believe that a cancer arising in the superficial layer of the skin will disrupt the local matrix of birefringent collagen fibers possibly with less birefringent cancerous material. Some speckle artifacts are visible in both images, these artifacts are caused by air bubbles between the camera optical flat and the skin. Water is used as a matching liquid.

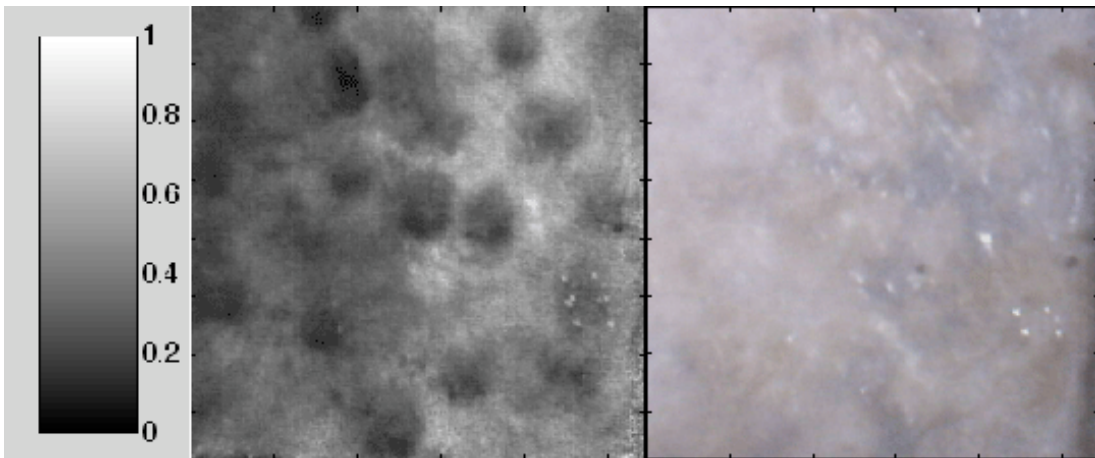


Figure 11: Image of a melanoma; on the left we show the polarized image on the right the Horizontal image

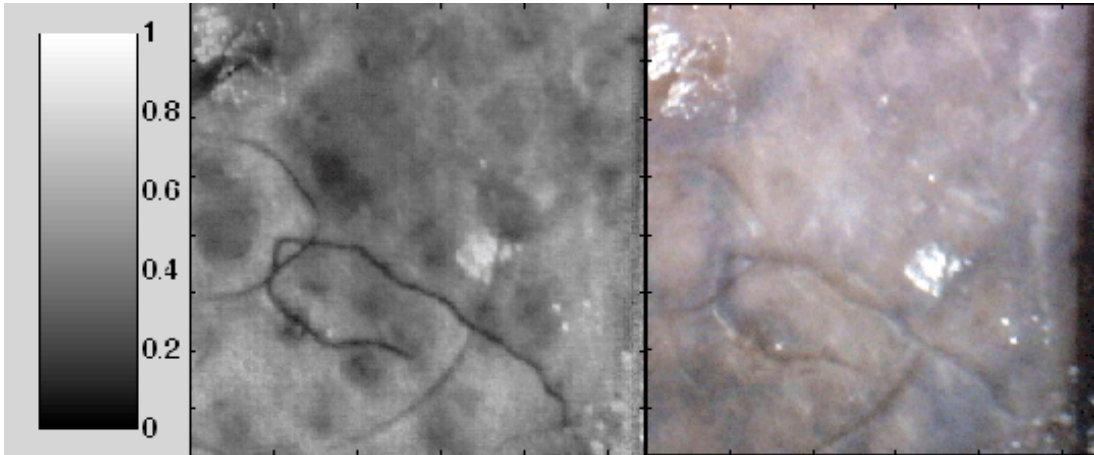


Figure 12: Image of a melanoma in situ; on the left we show the polarized image on the right the Horizontal image

## 5. CONCLUSIONS

We built a hand-held polarized light system that can acquire images of skin lesions in real-time. The hand-held system is small, can fit in the physician's hand, and can perform real-time acquisition using a custom-made software. Early clinical work is encouraging: results are comparable those obtained with a much more expensive and bulky system built with a high quality 16-bit camera<sup>5</sup>.

## 6. REFERENCES

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