A Snapshot Endoscopic Polarisation Imaging System

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INTRODUCTION

Polarisation of light has been proposed as a contrast mechanism for imaging the scattering properties of biological tissue. This includes depolarisation of light with depth and wavelength sensitivity of polarised light scattered by cells and nuclei. Changes in cellular density in *ex vivo* samples have been identified, distinguishing adenocarcinomas from healthy tissue [1]. Analysis of changes in linear polarisation has also been used to characterise dermal pigmented lesions *in vivo* [2] and identify structural changes in cervical tissue [3]. However, measurements require sequential acquisition of multiple images using different polarisation filters, which may take tens of milliseconds or more, depending on the number of polarisation states needed [3] leading to motion artefacts *in vivo*. For rigid endoscopy the analysing optics must be placed at the distal end of the instrument due to their complex polarisation properties [4]. Previous endoscopic implementations have used optical fibre probes inserted into flexible endoscopes scanned over the tissue [5] or highly specialised illumination optics, customised endoscopes and sequential imaging [6]. However, no fast rigid polarisation endoscope has yet been presented. In this paper, a modified da Vinci stereo endoscope is reported that allows simultaneous polarisation imaging of two orthogonal states using a conventional light source.

MATERIALS AND METHODS

A da Vinci endoscope (Intuitive Surgical, Inc., Sunnyvale, USA) has been adapted using a tip attachment to provide polarised white light illumination and detection through its stereo imaging channels. A schematic of the tip attachment is shown in Fig. 1.

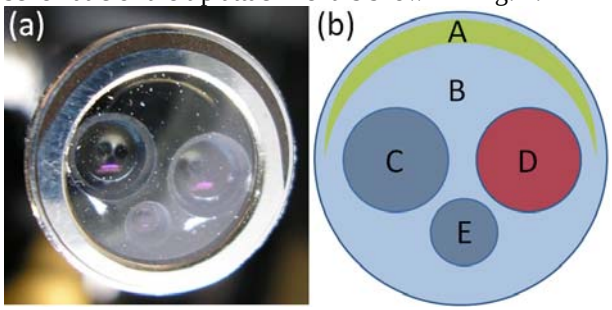

Fig. 1 (a) Tip of the da Vinci endoscope. (b) Polarisation endoscope tip attachment schematic. A: illumination fibre bundle, B: plate polariser, C: CO channel covered by plate polariser, D: CR channel covered by plate polariser and ¼ wave plate, E: unused imaging channel.

A 12.5 mm diameter plate linear polariser (FPC, CVI Melles Griot, UK) covers the entire end face of the endoscope including the illumination fibre bundle and both stereo channels. This filter is dichroic, with a high optical damage threshold (1 W cm^{-2} for polarisation perpendicular to the plate's orientation and 5 W cm^{-2} for parallel)[1] as light emitted from the xenon source at the endoscope tip may be close to 1 W. A ¼ wave plate was secured to the plate polariser using a thin bead of silicone adhesive so that it covered one of the stereo imaging channels. This wave plate rotates linearly polarised light by 90° before it passes through the plate linear polariser. The result is that one stereo channel detects light parallel to its incident polarisation (CO) while the other detects the perpendicular component (CR). Colour cameras (DCU 223C, Thorlabs Ltd., UK) recorded images from both channels simultaneously.

The CR and CO images were used to create an orthogonal states contrast (OSC) image [7] by detecting the relative amounts of parallel and perpendicularly polarised light reflected from the sample:

$$OSC = \frac{CO - CR}{CO + CR} \quad \textbf{(1)}$$

Equation 1 provides a measure of how much of the reflected light has retained its initial polarisation. If a smooth, highly reflective surface is illuminated, the reflected light will retain its initial polarisation, pass through the CO channel and be completely blocked by the orthogonal CR channel resulting in a high OSC. However, if the sample causes the light to be multiply scattered before travelling back to the endoscope, the randomisation of its polarisation will mean less CO light is transmitted and more CR light, reducing the OSC.

Since colour cameras were used for data acquisition, it was possible to examine the variation of the OSC signal in different spectral bands using the red, green and blue colour planes.

Initial results from the system are presented here showing images of objects with varying optical properties including skin (normal and nevus) and metal. Raw colour and OSC images in each colour plane are shown and the resulting OSC values analysed.

RESULTS

Figure 2 shows polarisation images of a finger with a metal ring. The raw colour images show that the regular

[1] https://www.cvimellesgriot.com/Products/High-Contrast-Plate-Polarizers.aspx

reflection of light from the surface of the skin and from the surface of the metal are sharply defined in the CO image. Rejection of this light in the CR image shows a loss of definition in the surface features of the skin and a significantly reduced reflection from the metal ring.

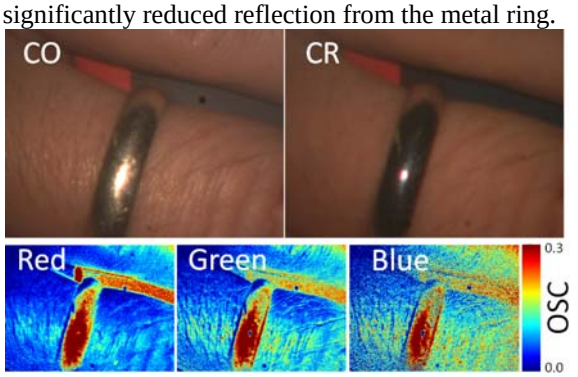

Fig. 2 Raw colour images of finger with metal ring in the CO and CR channels, along with OSC images calculated in the red, green and blue colour planes.

The OSC images in each of the three colour planes reveal the highest contrast on the metal ring, where the incident polarisation has been maintained, while the surrounding skin is much lower. Within the surrounding skin however, there appears to be a slight increase in OSC from the red to the blue colour planes along with an increase in noise.

A small lightly pigmented nevus in the skin is shown in Fig. 3, which is faintly visible in the raw colour images. Again, the sharp surface contours of the skin's surface are visible in the CO image but not the CR image.

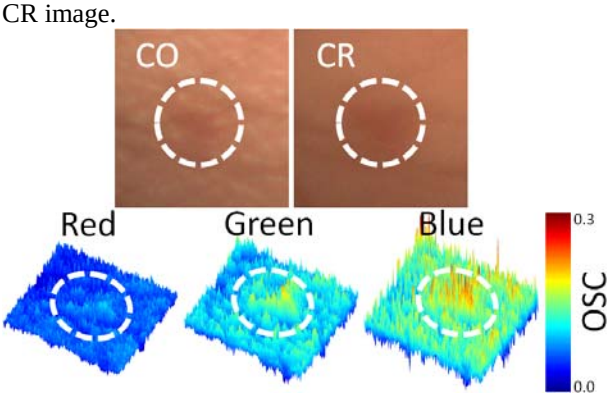

Fig. 3 Raw colour images of a small pigmented nevus in skin in the CO and CR channels. The OSC images show that the signal from the nevus becomes more visible in going from red to blue.

The OSC signal from the area containing the nevus increases from the red (where it is invisible) to the blue regions of the spectrum (visible but noisy).

DISCUSSION

A da Vinci compatible stereo endoscopic system capable of acquiring OSC images in three spectral bands simultaneously has been presented. Light regularly reflected from skin tissue and a metallic object maintains its initial polarisation resulting in a high OSC. However, light that penetrates deeper into the tissue becomes randomly polarised, producing a lower OSC.

The observed increase in OSC from the red colour plane to the blue is explained by the fact that red light penetrates tissue deeper than green or blue due to relatively low absorption by blood. Therefore, a red photon will travel farther than a blue one and have a correspondingly higher probability of being multiply scattered and randomly polarised. Conversely, any blue photons re-emerging from the skin will have undergone less scattering and are more likely to retain their initial polarisation, resulting in a higher contrast.

Wavelength-dependent effects are also evident in the lightly pigmented nevus as red light penetrates deeper into the region of high melanin content than green or blue, becoming depolarised and resulting in a low OSC of a similar value to the surrounding skin. Higher absorption of green and blue light ensures that only superficially penetrating photons are reflected from the nevus resulting in higher OSC.

Future work will focus on obtaining images of tissue during surgery and identifying superficial microvasculature structures that would be otherwise difficult to visualise using conventional endoscopic imaging. Calibration of the stereo cameras will also be carried out to automatically register the CR and CO images and correct for radial distortions. This would also allow quantification and correction of the disparity between each view due to their 5 mm separation, which may become significant at very close working distances.

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