Polarised stereo endoscope and narrowband detection for minimal access surgery

Neil T. Clancy,1,2* Shobhit Arya,2 Ji Qi,1,2 Danail Stoyanov,3 George B. Hanna,2 and Daniel S. Elson1,2

1Hamlyn Centre for Robotic Surgery, Institute of Global Health Innovation, Imperial College London, SW7 2AZ, UK
2Department of Surgery and Cancer, Imperial College London, SW7 2AZ, UK
3Centre for Medical Image Computing, Department of Computer Science, University College London, WC1E 6BT, UK

*n.clancy@imperial.ac.uk

Abstract: Polarisation imaging has the potential to provide enhanced contrast based on variations in the optical properties, such as scattering or birefringence, of the tissue of interest. Examining the signal at different wavebands in the visible spectrum also allows interrogation of different depths and structures. A stereo endoscope has been adapted to allow snapshot acquisition of orthogonal linear polarisation images to generate difference of linear polarisation images. These images are acquired in three narrow bands using a triple-bandpass filter and pair of colour cameras. The first in vivo results, acquired during a surgical procedure on a porcine subject, are presented that show wavelength dependent variations in vessel visibility and an increase in contrast under polarised detection.

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1. **Introduction**

Analysis and manipulation of the polarisation properties of light reflected by tissue from a polarised input beam have been used to perform different types of biomedical measurements including sub-epidermal skin imaging [1], colon cancer margin detection [2], characterisation of skin lesions [3], and visualisation of tissues exhibiting dichroic or birefringent properties [4, 5]. It has also been suggested as a means of identifying abnormal tissue during surgery in conditions such as endometriosis [5] where endometrial tissue develops outside the uterus as lesions.

However, thus far most applications have focused on imaging of *ex vivo* tissue samples or the skin due to the difficulties attached to *in vivo* imaging, such as gaining access to sites of interest during surgery with optical instruments and motion artefacts during acquisition of the multiple images needed. The feasibility of using polarisation during a flexible endoscopy was demonstrated recently in a study of Barrett’s oesophagus where crossed-polarisation was used to improve the visibility of the microvasculature [6]. Quantitative endoscopic tissue polarisation characterisation using a custom-built laparoscope has also been investigated in *ex vivo* tissue [7, 8]. However, signal level, motion artefacts and acquisition speed remain a challenge for *in vivo* use. Additionally, some current widely-used standard endoscopes contain birefringent optics, which alter the polarisation properties of light in a way that may not be reversible [9].

Of the quantitative polarisation imaging techniques presented in the literature many use the difference of linear polarisation (*Pol*) due to its relative simplicity, since the polarisation state analyser needs just two polarisation states [3, 10–12].

A tip attachment for a stereo endoscope has recently been proposed to acquire difference of linear polarisation images from tissue in a single snapshot with LED illumination [13]. In this paper a customised tip attachment for the endoscope is used with a xenon light source and triple bandpass filtered detection to perform narrowband endoscopic polarisation imaging of tissue. The transmission properties of the polarisation filters used are characterised before showing the first intraoperative results acquired using the system during open surgery on a porcine subject.

2. **Materials and methods**

2.1 **Polarised stereo endoscope**

A schematic of the experimental set-up is shown in Fig. 1. A 12 mm-diameter rigid stereo endoscope (Intuitive Surgical, Inc., Sunnyvale, USA) with a 5 mm baseline (centre-to-centre separation of the objective lenses at the tip) and a pair of synchronised colour CCDs (DCU223; Thorlabs Ltd., UK) was used to acquire parallel- (CO) and cross-polarised (CR) images of tissue simultaneously. The polarisation optics consisted of a film linear polariser (‘TechSpec visible linear polarizing laminated film’, Edmund Optics, Inc., USA) as shown in Fig. 1(a). A 5 mm diameter circular section was removed and replaced with its transmission
axis rotated by 90°. Figure 1 shows the modified filter, which was held in place, without adhesive, by a 1 cm long rubber tube cut with appropriate-sized slots.

![Image of stereo polarisation endoscope](image)

**Fig. 1. Stereo polarisation endoscope.** (a) A piece of film linear polariser placed over the endoscope face generates linear polarised light. The CO component is detected through the right channel while a separate section with its transmission axis orientated at 90° collects CR light. (b) Light passing through the endoscope’s CO and CR channels exits through the eyepieces at the proximal end and is focussed onto the CCDs, through a triple bandpass filter, using 50 mm focal length lenses. (c) Combined transmission properties of the triple bandpass filter and the colour CCD’s RGB Bayer filter, which is used to separate the three bands.

Narrowband operation was implemented using a xenon light source (Xenon 300; KARL STORZ GmbH, Tuttlingen, Germany) and a multiple bandpass filter (69008M, Chroma Technology Corp., USA), placed in front of the CCDs, to produce three bands with a full-width at half-maximum (FWHM) of approximately 25 nm centred on 470 and 535 nm, and with a larger 60 nm FWHM centred at 635 nm. These bands were separated using the RGB channels of the colour CCDs, which resulted in a spectrum that was the combination of the bandpass and Bayer transmission characteristics shown in Fig. 1(c). Light was coupled into the endoscope using a fibre optic light cable (KARL STORZ GmbH, Tuttlingen, Germany) with a 5 mm diameter active area. Light was transported within the endoscope from the illumination port via an internal tapered fibre bundle, terminating in a crescent-shaped region of approximately 11 mm² at the endoscope’s tip.

2.2 Characterisation

The transmission and extinction properties of the polarising film used in the tip attachment were characterised using a xenon light source and spectrometer. The light was coupled into a light cable and then directed, through an air gap, into a detector optical fibre connected to a spectrometer (USB HR4000; Ocean Optics, Inc., USA). A reference spectrum was acquired, then the polariser was placed between the light cable and detector fibre to acquire the test spectrum. The transmission properties of the film at each wavelength were then calculated using the ratio of the test to the reference values. Further test measurements were made with a set of co-polarised and cross-polarised films in front of the detector.
2.3 In vivo surgical imaging

Images of the porcine abdomen were acquired during open procedures on a 45 kg domestic white pig. The procedure was conducted under UK Home Office personal animal licence (PIL) No. 70/24843 and project licence (PPL) No. 8012639. Tissue imaged included the large and small intestine, and the bladder. The tissue was imaged at a 5 cm working distance, with camera exposure time set to 150 ms.

2.4 Image analysis

Due to the separation of the stereo imaging channels there was a disparity between the CR and CO images which increased as working distance decreased. As a result each pair of images had to be aligned prior to polarisation analysis. Since the tissue may have an arbitrary shape with complex curvature and depth, a particular point on the surface will be seen at a different object distance for each camera. A simple single translation, rotation or magnification correction could not be used in this case so a sparse feature tracking method, developed for use with multispectral image stacks [14, 15], was employed. A triangular mesh was overlaid on a reference image and a number of salient features detected. This step was repeated for the second image and the corresponding features were located, warping the mesh in order to align each pair. The process is illustrated in Fig. 2.

![Fig. 2. Registration of CO and CR images using the image warping algorithm. (a) Reference image (b) Equalized intensity (c) Mesh application and feature detection (d) Warped image.](image)

Maps of the difference of linear polarisation (\(Pol\)) were calculated at each pixel location in the aligned images using Eq. (1):

\[
Pol_\lambda = \frac{CO_\lambda - CR_\lambda}{CO_\lambda + CR_\lambda}
\]

where \(\lambda\) is the wavelength band of interest. For display purposes the \(Pol\) images in each waveband were then used to create a pseudocolour image by using them as the colour planes in an RGB image. This resulted in an enhanced colour image (\(Pol_{RGB}\)) that combined spatial and depth information, with non-depolarising structures appearing red when deeper and appearing green or blue when more superficial.
3. Results

3.1 Characterisation

The transmission spectra acquired for the polarising film are shown in Fig. 3. A single polarising film has a transmission of 32 ± 2% across the visible spectrum. This falls to 20 ± 2% for two co-polarised filters, and 0.1 ± 0.3% for cross-polarised (with some leakage of light at the blue end of the spectrum, between 400 and 450 nm, of 0.8 ± 0.3%).

![Fig. 3. Polarising film transmission spectra for a single polarising filter, and a pair of filters in CO and CR configurations.](image)

3.2 In vivo surgical imaging

Images of porcine large intestine are shown in Fig. 4. The most noticeable aspect of the stereo pair is that specular highlights, due to regular reflection from the tissue surface, are significantly attenuated in the CR channel. Also, the cross-polarised tissue image appears to be more red than for the co-polarised image due to an increase in the visibility of the microvasculature. A higher relative red intensity (R/[R + G + B]) is measured in the CR image (10%) than in the CO across the entire field-of-view.

![Fig. 4. Images of porcine large intestine viewed through the CO and CR channels. Specular reflections are noticeably reduced in CR and the visibility of a number of blood vessels (white arrows) has increased. The curvature visible at the edges in the CO image is due to the warping involved during the registration process.](image)

In order to extract tissue structural information the \( Pol \) value at each pixel was calculated. Figure 5 shows example processed \( Pol \) images in each of the three wavebands (R, G, B) acquired using the system. In each case the contrast value at each pixel is encoded with a greyscale value that varies from black (\( Pol = 0 \)) to white (\( Pol = 1 \)). Total intensity \( I_{Tot} = CR + \)
CO) images were also generated to simulate the response of a standard endoscope viewing the tissue using randomly polarised light.

![Figure 5](image_url)

**Fig. 5.** Pol images of porcine tissue in the red (R), green (G) and blue (B) wavebands along with the corresponding total intensity ($I_{tot}$) colour image. The data show varying contrast with wavelength in (a) bladder, (b) large intestine, and (c) small intestine.

An initial inspection of the processed images reveals that the Pol images have a more homogeneous appearance in the red channel, while vascular structures start to become more apparent in the green and blue. There is a general increase in noise levels in the blue channel due to high absorption by haemoglobin in the 440-500 nm region. Specular highlights present in the CO data, such as those in Fig. 5(a), are visible as high Pol artefacts in the processed images.

In Fig. 5(b) an area of relatively dense small vessels is visible in the top-left of the G and B channels, characterised by higher Pol in the microvasculature, along with increased visibility of smaller vessels in the bottom-left and bottom-right of the same images. Although mainly uniform, some higher Pol values are apparent in the R channel in image (c), particularly in the bottom-right of the Pol$_B$. This corresponds to the location of larger mesenteric vessels which extend further below the surface than the smaller ones seen in the rest of the image.

Using the data from the individual Pol images shown in Fig. 5 the corresponding Pol$_{RGB}$ images were generated and are displayed in Fig. 6. In general these images are dominated by blue/green colours in vascularised areas, which indicate that linearly polarised red light becomes randomly polarised more readily than the other spectral bands. The pseudocolour representation highlights vascular features that are not apparent in the conventional colour images such as densely-arranged vessels (a), microvasculature (b, c), and the structure of the vasa vasorum (e). There is also a strong signal in the red colour plane of Fig. 6(e) indicating that dominance of a sub-surface feature over those seen at depths probed by blue and green.
Fig. 6. Standard colour and enhanced PolRGB images. Polarisation information is encoded in colour with red representing the signal from deep structures and blue/green corresponding to more superficial tissue. (a)-(c) Small bowel (d)-(f) Bladder (g)-(h) Large bowel. White arrows indicate vascular features whose visibility has been enhanced.

A contrast-to-noise analysis was performed on the acquired images to quantify the change in visibility of vascular features from the background tissue. Pol images were compared with standard total intensity images to quantify the change in visibility of the vasculature in the bowel and bladder. Regions of interest corresponding to vessels and their neighbouring background tissue were analysed in a Weber contrast ($C_W$) measurement, defined by Eq. (2):

$$C_W = \frac{|I - I_0|}{I_0}$$

(2)

where $I$ and $I_0$ are the mean intensities of the vessel and the background tissue, respectively. The results in Fig. 7 show an improvement in contrast in the Pol images when compared to the standard total intensity image.
Fig. 7. Contrast analysis. (a) and (c) show PolRGB ROIs in the bladder and large bowel, while (b) and (d) are the total intensity RGB images for the same regions. The bar chart (e) shows the difference in Weber contrast between vessels of varying size and immediately neighbouring tissues for standard total intensity and Pol images (green waveband) of the bladder, and large and small bowel.

In the green waveband there is an observed average increase in $C_W$ of 879% for the vessels surveyed, which falls slightly to 867% in the blue range. The visibility of all but the largest vessels in the red region was so low, as can be seen from Fig. 5, that a meaningful contrast measure was not possible.

4. Discussion

The first in vivo surgical results from this endoscopic polarisation imaging system demonstrate contrast enhancements based on absorption and scattering of light. The CR channel provides depth gating by rejecting the polarisation-maintaining specularly or superficially-reflected light and detecting the multiply scattered randomly-polarised signal. In the CO channel this diffusely reflected signal is also present, along with specularly reflected light, which retains its initial polarisation direction and photons that have penetrated the surface but have undergone a very small number (less than 10) of scattering events before re-emerging [16]. The depths from which these superficial photons may be detected is therefore dependent on the scattering properties of the tissue and the wavelength of the light used. The differential Pol images thus probe a superficial layer of tissue whose thickness is a function of wavelength.

In the visible light spectrum both absorption and scattering mean free pathlengths increase with wavelength, meaning that the average depth of tissue interrogated in the red band is greater than that in the green or blue bands. This is apparent in Fig. 5 which shows that the visibility of blood vessels changes from the R to the B channels. The overall Pol values in the red channel are homogeneous and low due to the fact that red light has the highest penetration depth of the three wavebands used. Since the scattering coefficient is dominant over absorption this means that these photons also have the highest probability of being scattered multiple times and becoming randomly polarised. At short wavelengths, absorption by haemoglobin is one to two orders of magnitude greater than in the red region, and limits the penetration depth of blue and green light. Due to this high absorption any light reflected from superficial blood vessels is more likely to have been scattered a very small number of times and to have retained its polarisation orientation. This results in the high Pol value seen in the
blood vessels in Fig. 5 and Fig. 6. In the red channel there is also some signal that may be due to the presence of deeper-lying blood vessels, as seen in Fig. 5(c). In Fig. 6(e) there is an elevated Pol value in the red channel indicating the presence or extent of a vessel or scattering structure at a greater depth than those visible in the G and B columns of the same piece of tissue.

Based on simulations by Liu et al. [17] the polarisation-maintaining signal comes from a volume of tissue with an optical depth ($\tau = (\mu_a + \mu_s)D$, where $D$ is the geometrical thickness of the tissue, and $\mu_a$ and $\mu_s$ are the absorption and scattering coefficients, respectively) of approximately 3 for wide-area reflection collection. Using the averaged scattering data and estimated typical absorption coefficients for soft tissues, shown in Table 1, from a recent review of optical properties [18] the estimated values of $D$ are 168, 199 and 247 $\mu$m for the blue, green and red bands, respectively.

| $\lambda_c$ (nm) | $\mu_s$ (cm$^{-1}$) | $g$ | $\mu_a$ (cm$^{-1}$) | $\mu_s'$ (cm$^{-1}$) | $D$ (\mu m) |
|-----------------|--------------------|-----|---------------------|----------------------|-------------|
| 470             | 178.16             | 0.9 | 0.53                | 17.82                | 168         |
| 540             | 149.98             | 0.9 | 0.40                | 15.00                | 199         |
| 640             | 121.49             | 0.9 | 0.03                | 12.15                | 247         |

The Pol images have the effect of increasing the visibility of superficial blood vessels in the tissues inspected using the endoscope. Compared to the corresponding total intensity images, which are analogous to standard unpolarised images, the Pol images demonstrate a significant increase in the Weber contrast of vessels of varying size. It is worth noting that, due to the presence of the bandpass filters, the total intensity colour images are constructed from three narrow bands. This alone produces an image which would be expected to give an improved contrast over conventional cameras fitted with broad RGB filters. Therefore, the potential increase in contrast achievable with polarisation imaging over standard systems could be expected to be even greater than that measured here.

A number of system limitations exist and are responsible for artefacts in the processed images. Specular highlights cause pixel saturation in the CO images due to direct reflections from the tissue surface and render these pixels unusable for Pol calculations. However, the CR channel suppresses these effects significantly and improves visibility of the vasculature. The visual impact of remaining highlights may be reduced using inpainting techniques [8] but any fine structures present within and around these areas will be ‘washed out’. The registration step required to correct the disparity between the stereo channels was carried out offline during these experiments. A real-time implementation of this algorithm will be required for a clinical system. The current system is also hampered by poor light throughput, with a large penalty incurred by the polarisers alone. The low damage threshold of the plastic polarising material further limited the allowable light power used. Custom-cut high damage threshold polarisers will allow the use of higher light powers, with greater light throughput. This will also improve the signal to noise ratio in the images and allow imaging at greater working distances where stereo disparity becomes negligible. Even for the working distance used in this paper of 5 cm, the small baseline between the imaging channels and the slowly varying signal strength for the cross-polarised channel means that the disparity between the channels is unlikely to have a significant effect on the polarisation signals.

Previous work by other authors has demonstrated that rotation of the direction of the input polarised light may result in variations in the reflected signal in tissues with a high degree of anisotropy, such as tendons and muscle [4]. However, the tissue examined in this paper was, by comparison, structurally homogenous and isotropic. This is supported by previous work by our group and others [8, 19], which has shown that depolarisation dominates over retardance and diattenuation, making it unlikely that additional contrast would be seen by rotating the incident polarisation angle. Indeed, Mueller polarimetric analysis of bowel tissue has shown it to be a partial depolariser with insignificant diattenuation and retardance [20]. Possible
sources of a birefringent signal, such as the muscle layers of the small bowel, may have been beyond the penetration depth of the system. In a previous *ex vivo* rodent study the bowel was indistinguishable from other organs in the abdomen based on diattenuation, but the stomach, with its thick muscular wall, did show a potential signal in this regard [8].

6. Conclusions

This paper has presented an endoscopic system capable of acquiring co- and cross-polarised light images of tissue during surgery using a stereo endoscope modified with a polarising filter tip. Depth gating of photons is achieved by generating differential Pol images, which are free from motion artefacts due to the synchronous detection of the imaging channels. Placing the polarisation state generator and analysers at the tip also avoided any possible polarisation artefacts associated with the endoscope optics, such as birefringence (in rigid endoscopes like that described here) or randomisation of polarisation (in fibre-based flexible endoscopes). A simple tip attachment constructed from plastic sheet polarisers demonstrated good achromatic performance but was subject to thermal damage due to absorption of the endoscope light when operating at higher powers. Future implementations of the design will incorporate custom-cut high damage threshold glass polarisers capable of withstanding these higher powers.

The use of multiple detection wavebands made it possible to probe different tissue volumes, revealing structures present at varying depths. Images of porcine bladder and bowel *in vivo* demonstrate that most of the signal from the vasculature is visible in the more superficial green and blue channels. Larger and deeper-lying vessels are visible in the red, which otherwise displays homogeneously low Pol values due to stronger randomisation of polarisation. Visibility of the vasculature was shown to improve in all imaged tissues using the Pol visualisation, with large increases in Weber contrast. Artefacts present in the image are generally caused by strong specular highlights present in the CO channel.

In order to detect anisotropic tissue structures future work will involve redesigning the endoscope so that the angle of the input polarisation state can be varied dynamically to highlight changes in tissue anisotropy. Optimisation of the angle for an arbitrary tissue orientation will allow the maximum contrast to be obtained. This offers potential applications in the detection of diseases that disrupt tissues with a known birefringent signal, such as collagen and elastin.

Potential applications for this system include detection of superficial lesions with low inherent contrast under standard endoscopic imaging, such as peritoneal metastases or endometriosis. In this type of tissue, local variations in scattering properties due to cellular abnormalities or hyperangiogenesis of the microvasculature could potentially be detected using the Pol signal. The detection of such peritoneal lesions will influence the stage of the disease and consequently the selection of management strategies.

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