Polarization response measurement and simulation of rigid endoscopes

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Abstract: Polarized light can reveal diagnostic information about tissue morphology. To promote easy adoption of polarization imaging techniques in the clinic it would be beneficial if they can be used with standard medical imaging instruments such as rigid endoscopes. We have characterized the polarization properties of two commercial laparoscopes and observed birefringence effects that complicate polarization imaging. Possible solutions are discussed that may be of interest to other tissue polarization imaging researchers.

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OCIS codes: (170.0110) Imaging systems; (170.2150) Endoscopic imaging.

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1. Introduction

Several studies have shown that the interaction of polarized light with tissue can reveal additional information compared to standard unpolarized illumination. For instance simply viewing tissue under crossed polarizers will reduce specular highlights and increase the contrast between tissues [1], whereas fully characterizing the interaction of polarized light with tissue can reveal changes in its bulk structure caused by cancer or necrosis [2–5]. Light-scattering spectroscopy uses Mie-theory calculations to recover the average size of cell nuclei, which changes as tumours progress [6, 7]. Polarization techniques provide morphological information and hence complement fluorescence, Raman or absorption sensing which reveal functional or metabolic information. Imaging these properties over a wide area will give clinicians a tool for assessing the boundaries between different tissue states. This is currently a complicated clinical task that requires a thorough visual examination, use of pre-operative medical imaging data or intra-operative biopsies depending on the procedure.

As with many biophotonics technologies, translating polarization imaging systems from the lab to the clinic raises many practical issues, partly because many current systems use a transmission geometry where the sample is located directly between the illumination source and the camera. Whilst useful for ex-vivo samples or small animal imaging this is not feasible for imaging organs in-vivo. Simple reflection geometries [3] are suitable for imaging skin but cannot image inside the body except during open surgery. Minimally invasive endoscopic techniques have been widely adopted in modern medicine due to better patient outcomes. The simplest way to bring polarization techniques into the clinic is to incorporate them into current endoscopic surgery instruments. We have previously used a rigid laparoscope to perform polarization spectroscopy, but after noticing interference fringes we have carried out a full polarization characterization of two commercial laparoscopes, one of which is shown in Fig. 1.

2. Methods

2.1. Rigid Endoscopes

We briefly outline the construction of rigid endoscopes in order to describe the polarization properties observed. Rigid endoscopes have superior image quality compared to flexible endoscopes as the rod lens relay system gives better light transmission than a fibre bundle. They are commonly used for procedures inside the abdominal cavity where they are called laparoscopes. We obtained two laparoscopes from prominent manufacturers, one from Karl Storz GmbH (10 mm 0° viewing angle, part no. 26003 AA) and one from Olympus Ltd (10 mm 0°, part no. A5254A). Similar considerations described in this paper apply to other rigid endoscopes, e.g. cystoscopes and arthroscopes as the fundamental design is the same.

The optics of a laparoscope can be divided into an objective lens, the rod lens system and an eyepiece. A schematic representation is shown in Fig. 1. The objective lens at the distal end demagnifies the incident image so it can be passed into the relay system. The relay system comprises several sets of rod lenses which allow parallel rays from image points to travel with shallow angles. This increases the distance a ray travels inside the lens without intersection with the laparoscope tube and reduces the number of lenses required. Finally the proximal eyepiece creates approximately parallel rays out of the laparoscope so the eye or another lens can bring them to focus. Both the distal and proximal lenses are covered by windows that can withstand
Fig. 1. The Olympus 0° forward-viewing laparoscope characterized in this experiment (top), and a schematic showing a cross section (bottom). The length is 500 mm and diameter 10 mm. The proximal end is on the left and distal tip the right. Illumination light is directed by fibre optics to the tip. Light reflected from tissue is then imaged by the objective lens, relayed via the rod lenses and then transmitted to the viewer at the eyepiece. Hard windows that can withstand sterilization cover the entrance and exit to prevent contamination. The Karl Storz laparoscope is similar in appearance.

the autoclaving process required to sterilize surgical instruments.

Illumination light is transmitted to the distal via a built-in fibre bundle with a connector at the proximal end as shown in Fig. 1. These fibres are not polarization preserving, hence to provide polarized illumination either these fibres must be replaced or a small polarizer must be mounted at the distal tip.

2.2. Measuring Polarization States

A Stokes’ vector $S$ describes a polarization state using four components which are generally labelled $I, Q, U,$ and $V$. These describe the illumination intensity, and then the difference between horizontal and vertical ($H$ & $V$), $+45°$ and $-45°$ ($P$ & $M$), and right- and left-hand circular ($R$ & $L$) polarization respectively, see Eq. (1). A Stokes’ vector can be calculated from just six measurements using a standard analyser, as the total illumination intensity is just the sum of any two orthogonal states (conventionally the horizontal and vertical states are used) [8].

Fig. 2. Experimental schematic. Laser light at 600 nm is incident on a diffuser to ensure even illumination. A rotatable polarizer and removable $\lambda/4$ waveplate are used to create linear and circular polarization states. This uniform polarization is then imaged by the objective lens of the laparoscope. A rod lens system relays this image to the eyepiece, where a chosen state is passed by the analyser. Finally a lens forms the image of the viewing field on the CCD.
The polarization effects of an optical component can then be described by a four-by-four Mueller matrix $M$ (1) which exhaustively details how each output polarization state depends on the input polarization state. To calculate the Stokes’ vector of a ray exiting a component the input vector is simply pre-multiplied by the Mueller matrix as in Eq. (2). Hence an identity Mueller matrix implies that the component does not interact with polarized light at all, and the left-most column gives the output state for input unpolarized light. In order to record a complete Mueller matrix 36 separate measurements are required [9]. This can be reduced to 18 by using some algebraic manipulation but we have chosen to record the full 36 measurements in order to average out noise [3].

$$S = \begin{pmatrix} I & Q & U & V \end{pmatrix} = \begin{pmatrix} H+V & H-V & P+M & R+L \end{pmatrix}$$

$$M = \begin{pmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{pmatrix}$$  \quad (1)

$$S_2 = MS_1$$  \quad (2)

A matrix was recorded for each pixel in the field of view using a CCD camera and the set-up shown in Fig. 2. This used rotatable sheets of linear polarizer (TechSpec, Edmund Optics) and removable $\lambda/4$ waveplates (CVI-Melles Griot) to create the relevant polarizer and analyser orientations. Malus’ law was used to establish a polarization reference frame consistent with the laboratory and hence the CCD camera. Laser light was reflected obliquely from a slide onto a power meter through the rotatable analyser that was rotated until the incident illumination was at a minimum. This was labelled as the ‘Vertical’ polarization direction with ‘Horizontal’ perpendicular. The rotatable polarizer was then aligned to the analyser. Once the reference frame had been established the polarizer and analyser were placed at either end of the laparoscope with sufficient space to insert and remove the waveplates as required. The CCD and lens were placed behind the analyser so that the whole field of view was brought into focus. A diffuser was placed behind the polarizer to create a more even illumination field.

The laser light was provided by a spectrally filtered supercontinuum laser source (Fianium SC400) [10]. The white light output of the laser was dispersed by a prism and focused onto a Digital Multi-Mirror Device (DMD, Texas Instruments Ltd.). Portions of the spectrum were selected by switching the DMD mirrors to reflect specific wavelengths through a second focusing lens into a liquid light guide (Karl Storz Ltd.). Liquid light guides are used widely to connect lamp sources to endoscopes instead of fibre-optic light guides as their saline cores are more flexible and durable.

For all but the most trivial optical interactions Mueller matrices can be hard to interpret. This effect is magnified if a single matrix contains the compound action of several components. Lu and Chipman previously showed that is possible to decompose a non-degenerate Mueller matrix into a set of matrices each representing a single optical effect [11]. From these Mueller matrices a single value can be calculated representing the depolarization ($\Delta$), retardance ($\psi$) and diattenuation ($D$) effects [12–15] as in Eq. (3). Depolarization is the decrease in the degree of polarization defined as $V = \sqrt{Q^2 + U^2 + V^2}/I$ due to effects such as scattering. The retardance is the additional phase difference introduced between two orthogonal polarization states. This effect is used in $\lambda/4$ waveplates to convert between linear and circular polarization. Diattenuation describes the difference in transmission between two orthogonal states. A linear polarizer is a perfect diattenuator as it completely passes one state while blocking the orthogonal state.

$$M = M_\Delta M_\psi M_D$$  \quad (3)
3. Results and Discussion

3.1. Measured Results

The measured Mueller matrices for the laparoscopes are shown in Fig. 3. Each sub-image shows one element of the Mueller matrix across the circular image field of the endoscope. To correct for the illumination intensity the elements are normalized to element $m_{11}$. Instead of showing the resulting unity image for $m_{11}$, we have normalized to its own maximum value in the figure to illustrate the illumination field. This shows a radial fall-off, as usually observed in endoscopes due to the uneven illumination and image apodization.

Uniform polarization effects across the field of view would result in elements of uniform value and hence flat images displaying no structure. This is clearly not the case as highly structured patterns are visible across the field of view, meaning the polarization properties change with image co-ordinate. The Olympus endoscope showed circular arcs in elements $m_{22}$ to $m_{43}$, which were observed to rotate and change value as the endoscope was rotated about its long axis [compare Figs. 3(a) and 3(b)]. The Karl Storz endoscope showed patterns with high amounts of

![Fig. 3. Measured Mueller matrices for the Olympus and Storz laparoscope (a)–(c) and a simulation for a sheet of sapphire (d). Each sub-image shows one element of the matrix across the whole field. Matrices were measured with the system illustrated in Fig. 2. The Karl Storz laparoscope patterns did not vary with the laparoscope orientation while the Olympus laparoscope did. Parts (a) & (c) recreated from [16].](image-url)
Both patterns exhibited a simple wavelength dependence, expanding outward as the wavelength increased (Not shown).

Both laparoscopes shared the property that elements $m_{12}$ to $m_{14}$ (top-row) and $m_{21}$ to $m_{41}$ (left-column) were zero. From this we can deduce that they do not contain polarizing elements and only interact with light that is already polarized. Therefore these effects are not apparent when illuminated using standard sources such as halogen lamps.

3.2. Simulated Results

In order to better understand where these effects may originate we considered the arrangement of rays passing through the entrance and exit windows of the laparoscopes as shown in Fig. 2. Rays originating from an image point are aligned approximately parallel to each other when they pass through the exit window with points at the edge of the image passing at greater angles. This is equivalent to the conoscopic geometry used in crystallography [17] and illustrated in Fig. 4. The important feature of this arrangement is that it directly interchanges image co-ordinates for angles passing through a sample. This allows the birefringence of a sample to be easily assessed at all angles, and any symmetry properties of the resulting conoscopic images are related to the orientation and symmetry properties of the crystal lattice. In our case the exit window is in an equivalent plane to the crystal sample.

The windows of the Karl Storz laparoscope are made from sapphire which is a birefringent crystal. To confirm that the observed patterns could be explained by this we simulated the Mueller matrix that would be expected in a conoscopic geometry if a thin sheet of sapphire had its slow axis aligned parallel to the optic axis. The half-angle of the field of view for the laparoscope was calculated as approximately $38.6^\circ$. A grid of angles matching this was created and used to find the effective refractive indices for the ordinary and extra-ordinary rays, which were subtracted to find the effective birefringence at a wavelength of 600 nm. The resulting Jones matrix was calculated using an assumed thickness of 0.5 mm for the sapphire sheet at all incidence angles. These were pre- and post-multiplied by the Jones vectors corresponding to the measurement polarizations to produce simulated images of a conoscopy experiment. The same technique as for the real experiment was then used to convert these into a Mueller matrix.
The Jones calculus was used as it simplifies calculations where only fully polarized light is used. The simulation is presented in Fig. 3(d) which shows closely matching patterns for the top left 3x3 sub-matrix with Fig. 3(c), however they do not match in the right-most column and bottom row (the elements of a Mueller matrix relating to circular polarizations).

This indicated that the $\lambda/4$ waveplates might cause the discrepancy between measurement and simulation as they are only used to measure these elements. Achromatic waveplates have an angular dependence on their retardance and so are not suited to imaging applications. The angular dependence means that at points away from the centre we are no longer dealing with purely circular polarization but some elliptical state. The Karl Storz matrix was decomposed using Lu and Chipman’s technique, shown in Fig. 5. The diattenuation and depolarization were approximately zero across the field of view, as expected. The retardance exhibited angular symmetry with a sinusoidal radial profile. However all of the parameters had X-shaped patterns where they were discontinuous. This effect is strongest at the distal end of the laparoscope as the rays from the object crossing the waveplate are at steeper angles than those at the proximal end.

We then simulated the retardance through a sheet of magnesium fluoride, a material used to make achromatic waveplates using the same technique as for sapphire above. The result is shown in Fig. 5(d) and demonstrates the same X-shaped zones. This implies that the waveplates do affect the measurement of the Mueller matrix and hence the mismatch with simulation. Using zero-order waveplates would reduce the angular dependence although they would introduce a wavelength dependence, meaning the results would only be correct close to the central wavelength of the plate.

The close match with the simulation of the sapphire sheet shows that the polarization effects of the Karl Storz laparoscope come primarily from the birefringent window material. We are currently unable to provide a similarly convincing explanation of the behaviour of the Olympus laparoscope. We are unaware of the exact window material used but the lack of any symmetry means that the windows cannot be made from a birefringent crystal oriented as a $\lambda/4$ or $\lambda/2$ waveplate, although the orientation dependence and interaction with circularly polarized light does display waveplate-like properties.

### 3.3. Possible Solutions

In order to use commercial endoscopes with polarized imaging any polarization effects must be calibrated and corrected. In theory this can be done simply by measuring the Mueller matrix of a particular laparoscope before use in theatre, and provided this matrix is not degenerate its inverse could be post-multiplied by any Stokes’ measurements made through the laparoscope to extract the polarization state at the distal tip. When no circular polarizations are present in a system it is possible to use just a three-by-three Mueller matrix and consider only the lin-
ear states. However the birefringent nature of the crystals used means that most rays exiting the endoscope will have a circular component, and this cannot just be ignored. Hence the full Mueller matrix would have to be measured for every pixel in the image and at all wavelengths used in the system. But as described above achromatic waveplates have a strong angular dependency, whereas zero-order waveplates have a strong wavelength dependency. This means that the circular components of the Mueller matrix cannot be measured accurately for all pixels and wavelengths.

A simpler way of removing the polarization effects would be to remove the birefringent crystals and replace them with non-birefringent alternatives. Unfortunately simple fused silica is unsuitable since the bonding agents used with it cannot withstand the autoclave sterilization process. A good alternative would be diamond, as this uses the same bonding materials as sapphire but is not birefringent.

4. Conclusions

Current commercial laparoscopes are difficult to use with polarized light due to the birefringent materials used for the entrance and exit windows. Limitations in the characteristics of the waveplates necessary to measure circularly polarized light complicates the calibration of the polarization response using a Mueller matrix. This will necessitate the use of new, non-birefringent rigid endoscopes in future work, allowing the simple measurement of polarization data in-vivo using an instrument already familiar to surgeons.

Acknowledgements

We would like to acknowledge Karl Storz GmbH for the loan of an endoscope system and the UK EPSRC and Technology Strategy Board grants DT/F003064/1 and EP/E06342X/1.