Optical Measurement of Anastomotic Oxygenation Dynamics

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Abstract: Oxygen supply is an important predictor of the integrity and viability of luminal structures after surgery. Multispectral imaging is used to study haemodynamics during small bowel anastomosis and arterio-venous fistula formation surgery.

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1. Introduction

A surgical anastomosis describes the joining of one luminal structure, such as the bowel, oesophagus or a blood vessel, to another such structure. Oxygen supply to the tissues at the anastomosis may be a predictor of tissue viability, healing and ultimately the integrity of the seal. However, current operative indicators of ischaemia can be ambiguous and unreliable. A tool capable of intra-operative quantification of oxygen supply to the tissue could be applied in a number of clinical settings and provide real-time feedback to the operator of critical anastomotic sufficiency.

During colectomy surgery to remove a segment of bowel the mesenteric supply is divided and thus, the new route of oxygenated blood to an anastomosed area can be compromised. If perfusion is inadequate or not reestablished once the anastomosis is completed then there is the risk of ischaemia [1], which can lead to anastomotic dehiscence and leakage of intestinal content into the abdomen with its associated complications.

In preparation for dialysis patients with end-stage renal failure may require creation of an arterio-venous fistula (AVF), the surgical connection of a large vein directly to an artery. Over a period of weeks the vein dilates and strengthens, providing a strong and readily accessible vessel for cannulation. In a large number of patients however, neointimal hyperplasia (NIH) develops near the anastomotic site, resulting in narrowing of the vessel lumen and, ultimately, fistula failure [2]. This adverse process may be related to oxygen delivery to the vessel walls [3]; a clearer understanding of oxygen dynamics within the blood vessel walls will help direct current surgical practice and achieve better outcomes.

In this paper a multispectral imaging (MSI) system is used as a method to study the oxygen supply to tissues during the formation of anastomoses. Results from porcine experiments during bowel and vascular surgery are presented, followed by initial results from the first use of the system in human patients during the creation of a forearm AVF.

2. Materials and methods

Multispectral imaging system

An MSI system has been developed for use in both laparoscopic and open surgery settings [4]. It consists of a 30° laparoscope, monochrome CCD camera, liquid crystal tuneable filter and xenon light source, meaning that acquisition of the data cube is performed sequentially in the spectral dimension. To compensate for artefacts due to motion, such as breathing or peristalsis, a non-rigid registration is performed prior to spectral analysis [4]. For analysis of oxygen dynamics in bulk tissues a simple linear regression model was used to determine the relative quantities of oxy and deoxyhaemoglobin (HbO_2 and Hb, respectively) at each point in the field of view [5]. From this it was possible, subject to a number of assumptions, to calculate total haemoglobin (Hbt; the sum of HbO_2 and Hb) and oxygen saturation (SaO_2; the percentage of HbO_2 with respect to Hbt).

Surgical imaging

Spectral data were acquired from porcine subjects (50 kg domestic pigs; conducted under local research ethics approval) during bowel and vascular anastomoses using the imaging system to assess oxygen dynamics in the tissue. For the bowel experiment a laparotomy was carried out and a loop of small intestine exteriorised. Four multispectral data cubes were acquired in addition to a background measurement to correct for ambient light. A segment of the bowel was then removed following division of its mesenteric supply, before reattachment of the free ends using a hand-sewn end-to-end anastomosis technique. A further four MSI measurements were then made of the completed anastomosis.

As part of a separate vascular anastomosis procedure the carotid artery was isolated at the neck through a 12 cm incision and imaged with the MSI system, ensuring that the *vasa vasorum* were visible. Finally, the MSI system was used for the first time in a human case during AVF formation surgery (with local research ethics approval). The patient's brachial artery and cephalic vein were imaged in their native state after the initial dissection, and again after formation of the anastomosis. At this stage the vessels were briefly occluded in order to assess the component of the reflectance spectrum attributable to the oxygenation of the vessel wall as opposed to the oxygen carriage of the erythrocytes within the vessel lumen.

3. Results

Small bowel anastomosis

Figure 1 shows the results of the MSI data from the bowel experiment. Colour images reconstructed from the MSI data cube are shown alongside a composite image containing the SaO_2 map overlay, with its transparency weighted by blood volume (*Hbt*).

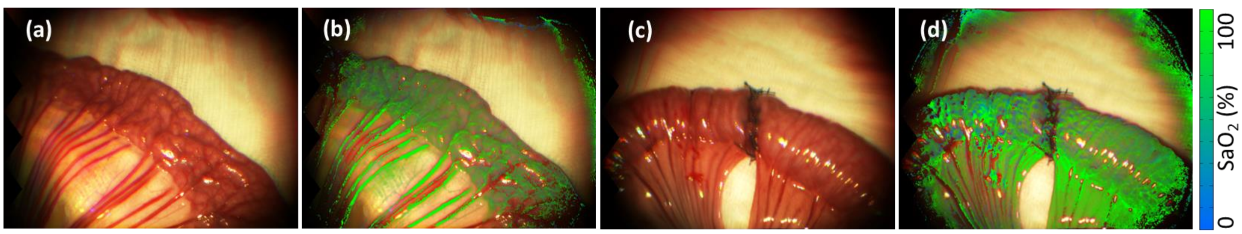

Fig. 1. Colour and composite SaO_2 maps of porcine small intestine before and after surgery. (a, b) Bowel segment in native condition. (c, d) End-to-end anastomosis.

Following completion of the anastomosis it can be seen from the oxygen saturation maps that perfusion to the bowel has been mostly maintained. However, in the peri-anastomotic region there is a measureable decrease in SaO_2. Three regions of interest (50×50 pixels) across the bowel were selected from three separate acquisitions from both the native tissue and anastomosis. Average values calculated from these regions show that there was a decrease in SaO_2 from 72±3% (baseline) to 48±12% (adjacent to the suture line).

AVF creation

Images of the porcine carotid artery are shown in Fig. 2 (a). The *vasa vasorum* are clearly visible in the walls of the vessel, and the average absorbance spectrum is given in Fig. 2 (b) along with the corresponding spectrum from non-vascularised areas of the arterial wall. To isolate the signal of the *vasa vasorum* from that of luminal blood the saturation was calculated using the average artery wall reflectance spectrum as a reference in an analysis method used previously in retinal oximetry [6]. The composite image in Fig. 2 (c) shows its spatial distribution.

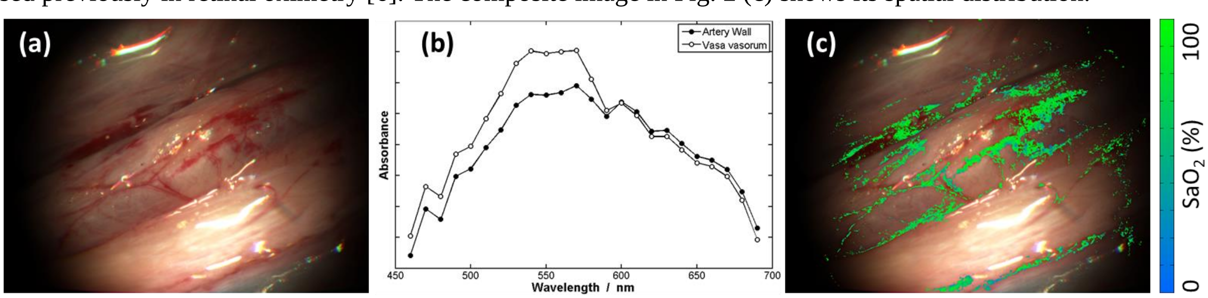

Fig. 2. Porcine carotid artery. (a) Colour image with the *vasa vasorum* clearly visible. (b) Absorbance spectrum of the vessel wall and the *vasa vasorum* (c) Composite SaO_2 map showing the oxygenation of the *vasa vasorum*.

Initial images captured during human AVF creation surgery are seen in Fig. 3 showing the artery in its native condition (a) and after the vein has been connected (b). The *vasa vasorum* were not clearly visible but average absorbance spectra were acquired from the artery in its native state (perfused) and immediately prior to removal of the vascular slings when the arterial lumen was clear of blood (Fig. 3 (b)). The spectra in Fig. 3 (c), uncorrected for light intensity, show a similarity in shape in the blue-green spectral region but some apparent differences in the red.

To test the effect of different parts of the spectrum probing different volumes of the vessel the absorbance spectra of Fig. 3 (c) were interrogated using the regression algorithm over a 60 nm moving window from the blue to the red end of the spectrum. Figure 3 (d) shows *Hbt*, a measure of blood volume, plotted against the central wavelength of this window. There is a clear divergence between the calculated *Hbt* in the perfused and flushed vessel that begins to appear above 580 nm, where the signal from the perfused vessel begins the rise and that of the flushed one falls.

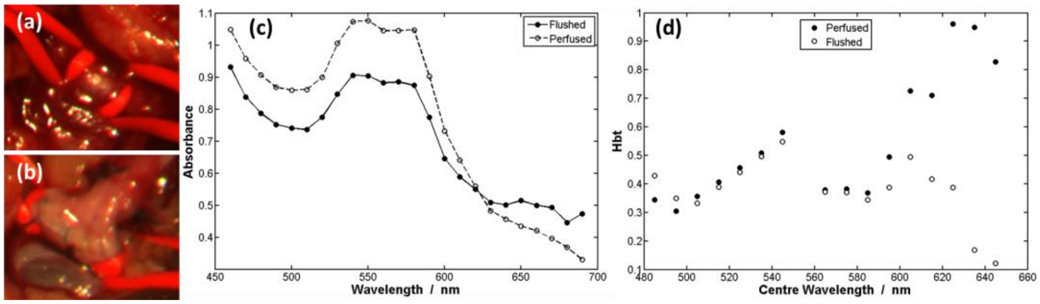

Fig. 3. Human AVF formation surgery. Colour images showing (a) the artery in its native condition and (b) after completion of the end-to-side anastomosis with the vein (before reperfusion). (c) Absorbance spectra of the artery with and without perfusion. (d) *Hbt* plotted against the central wavelength of a 60 nm sliding window in which the data from (c) was fitted.

4. Discussion and conclusions

A laparoscopic MSI system has been demonstrated for use in the assessment of haemodynamics during anastomosis formation in two different surgical scenarios. Initial measurements were made *in vivo* in two porcine experiments as well as during human AVF surgery. Reestablishment of blood flow to the anastomosed bowel ends was visualised using the system, and a drop in oxygen saturation was recorded in the peri-anastomotic region. In the second porcine procedure oxygenation of the *vasa vasorum* was quantified separately to the signal from blood inside the vessel.

Data captured from a patient during AVF surgery showed that differences in luminal blood volume (*Hbt*) were only apparent in the red end of the spectrum. This is consistent with the expected wavelength-dependent penetration depth of the wavelengths in question through human blood vessels. Red light was capable of sampling luminal blood and thus, reflecting the absorption change that arose when the vessel was flushed. The blue-green portion of the spectrum may only have sampled the vessel wall, whose blood content was unaffected. This type of spectral selection therefore has the potential to isolate changes in vessel wall oxygenation and correlate them with oxygen transport from luminal flowing blood.

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