Registration and analysis of multispectral images acquired during uterine transplantation surgery

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Abstract: Organ transplant success is dependent on blood supply health. A multispectral imaging laparoscope has been used to monitor tissue oxygenation changes during a rabbit uterine transplant. A feature tracking algorithm was used to compensate for movement.
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1. Introduction

The term 'infertile' is an all-encompassing term and includes women with absolute uterine factor infertility (AUFI) [1]. Uterine transplantation (UTn) has been proposed as a cure for permanent AUFI as result of loss of the uterus. A number of international groups are currently developing the surgical techniques in animal models, as summarised in a recent review [1], with the aim of eventually moving from the animal to the human setting. The vascular complexity of the organ means that re-anastomosis of its blood supply is a crucial step in UTn to allow reperfusion and ensure viability. It can also lead to an injury of a transplant, during ischaemia and reperfusion [2]. The current approach to monitoring this in the animal model is to use a pulse oximeter probe clamped onto the uterus to measure oxygen saturation and 'perfusion index' [3]. However, this only provides a point measurement of arterial oxygenation giving no spatial information on the overall supply to the tissue. Additionally, positioning and manipulating the probe and uterus is a practically difficult task, especially in smaller animals.

Here we describe a multispectral laparoscope which was used to acquire high resolution images of changes in tissue oxygen saturation during a uterine transplant procedure in a rabbit model. This technique involves using a white light source and tuneable filter to acquire images at many wavelengths in the visible range in order to build up a reflectance spectrum at each pixel [4, 5]. These spectra are then fitted using a linear regression model which uses the optical absorption of oxy- and deoxy-haemoglobin, from which their relative contributions are calculated. Previous implementations of this technique have also used hyperspectral data with numerical techniques to aid tissue visualisation and ischaemia detection [5, 6].

Depending on the spectral resolution required, camera exposure time and tissue albedo, a full acquisition may take several hundred milliseconds or more. Therefore, any movement of the tissue during this time will result in misalignment of the multispectral image stack. A registration algorithm is applied to the images to compensate for this motion prior to the spectral fitting in cases where organ motion was significant.

2. Materials and Methods

The instrumentation consists of a white light source (xenon 300, Karl Storz GmbH, Germany), liquid crystal tuneable filter (LCTF; Varispec, Cri, Inc, USA), laparoscope (0°, 12 mm diameter, Karl Storz GmbH, Germany) and monochrome camera (DCU 223M, Thorlabs Ltd., UK). Image acquisition and LCTF control were synchronised using software written in LabVIEW (National Instruments, Inc, USA). The LCTF was tuned from 440-720 nm in steps of 10 nm, resulting in 29 images for each acquisition. To compensate for the spectral shape of the light source, and the wavelength-dependent sensitivity of the camera and filter, a set of reference images of a reflectance standard (Spectralon, Labsphere, Inc, USA) were acquired and the average greyscale intensity over the target averaged to form a 'reference spectrum'. For each pixel in the multispectral stack the greyscale intensity was converted to reflectance by dividing by the reference spectrum. A schematic of the instrument is shown in Fig. 1.

Assuming that the dominant mechanism of light attenuation in the field of view is absorption by blood and that scattering is approximately constant across the wavelength range, the measured reflectance spectrum at each pixel is

a linear combination of oxy- and deoxy-haemoglobin. A multiple linear regression algorithm was implemented in Matlab (The Math Works, Inc, USA) to compute the relative fractions of both pure haemoglobin species [5, 7] and minimise the difference between the experimental reflectance and the predicted value. The oxygen saturation (SaO_2) was then calculated as the quantity of oxyhaemoglobin as a fraction of the sum of oxy- and deoxyhaemoglobin.

Fig. 1. Multispectral imaging laparoscope with xenon light source and control computer.

UTn commenced with exposure of the donor uterus following a mid-line incision. It was subsequently imaged with the left and right cornua, and fallopian tubes visible. The donor graft was removed *en bloc*, along with it blood supply. The aorta was cannulated, and the uterine specimen generously flushed with heparinised normal saline and perfusion solution (Custodiol HTK, Essential Pharmaceuticals, LLC, USA). It was then refrigerated (1 hour in the same perfusion solution, HTK, between 2°C and 8°C) while the recipient was being prepared. The recipient animal was anesthetized and prepared in a similar manner to the donor and its native uterus removed. The vagina was anastomosed initially to ensure proper orientation and positioning of the specimen followed by vascular re-anastomosis. The uterine horns were finally rejoined and the whole organ was imaged.

Motion artefacts introduced by breathing, peristalsis and relaxation of the tissue during the imaging period were corrected using a registration algorithm. Recently, fast techniques for the detection and tracking of deformable surfaces using sparse feature correspondences have been reported [8]. The advantage of these methods is that any sparse matching strategy can be used to achieve robust performance in the presence of large deformations and complex illumination conditions. The effectiveness of the approach has been demonstrated for tracking the motion of the beating heart endoscopically [9]. In this study, we use a similar strategy to [9] where features are detected and tracked across images from different wavelengths. To avoid trying to match disparate spectrums that have very different image appearance we propagate the solution from one wavelength onto the subsequent acquisition.

3. Results

In cases where motion of the organ was significant enough to cause misalignment of the multispectral stack and introduce artefacts, the image registration approach described above was used. This could successfully correct for movements which caused blurring of blood vessels for example, as shown in Fig. 2.

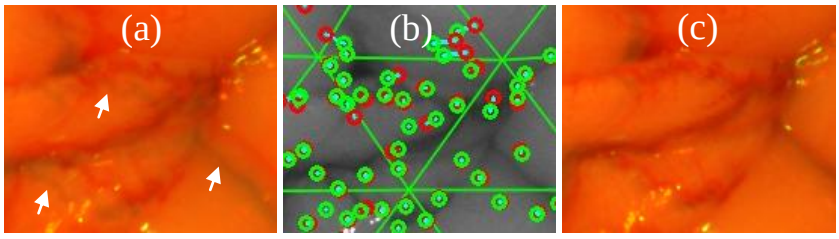

Fig. 2. Colour images of a section of uterus reconstructed from the full multispectral stack. (a) Organ motion is visible as blur and is especially noticeable around the blood vessels (indicated by arrows). (b) Feature detection and tracking in multispectral space. (c) After registration the vessels are correctly aligned and blur reduced.

Following the re-anastomosis, the uterus was observed to undergo a colour shift during reperfusion from its blanched appearance after flushing to a more reddish colour. The processed SaO_2 images for the donor uterus before and after transplantation are shown in Fig. 3 along with colour images reconstructed from the multispectral data after integration under the RGB filter transmission response of a digital colour camera.

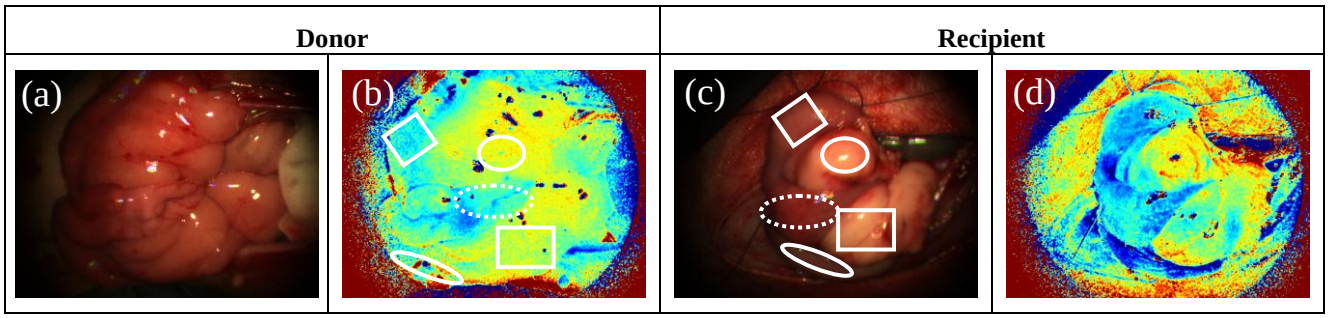

Fig. 3. Reference tissue oxygen saturation images of rabbit uterus (b) in the donor animal and (d) after transplantation. RGB images of the organ are also shown (a and c). The SaO_2 images are displayed using a colour scale that ranges from '0' (dark blue) to '1' (bright red). Corresponding sites on the uterus before and after transplantation are indicated by the white-outlined regions in (b) and (c).

The pre-transplant images show that the organ is well perfused in the donor animal, with high oxygen content in both sides of the uterus. The area of low saturation in the centre may correspond to a less vascularised area or possibly an area with a higher venous to arterial supply ratio. The post-transplant images show similar features after blood supply is re-established from the aorta. Areas of low SaO_2 correspond to connective tissue where re-perfusion is expected to take the longest. As before, the uterine horns in the post-transplant recipient have lower SaO_2 than in the donor. Previous experiments by our group using pulse oximetry on the uterus showed baseline readings of 95% in the donor and ranging from 60-90% in the recipient during the period following re-anastomosis. Using this technique, the same pre- and post transplant readings were 60±3% and 48±6% respectively.

4. Conclusions

A multispectral imaging laparoscope has been demonstrated as a potentially useful tool during UTn. It enabled monitoring of tissue oxygen saturation over the entire visible section of the organ in a non-contact method. Image warping allowed correct alignment of the multispectral data in order to remove artefacts due to motion of the tissue during acquisition. As with previous measurements using pulse oximetry, measured values of tissue SaO_2 show a decrease after transplantation. The absolute values of SaO_2 are much lower however. This may reflect the fact that pulse oximeters measure arterial SaO_2 only, while this imaging method also takes the venous side into account in addition to areas of the tissue that are not well-perfused, reducing the mean value. Specular highlights present in the image also have the effect of introducing spurious readings. Future work will introduce a scattering term to the model as the current assumption of a flat scattering spectrum may be contributing to underestimating SaO_2 as the optical pathlength is longer in the blue end of the spectrum than the red.

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6. References

[1] M. Brännström, C. A. Wranning, and A. Altchek, "Experimental uterus transplantation". Hum Reprod Update, 16, 329-345. (2010).
[2] G. Del Priore, S. Schlatt, R. Wagner, E. Reynoso, and J. Malanowska-Stega, "Uterus transplantation: on the edge". Semin Reprod Med, 29, 55-60. (2011).
[3] P. Moxey, K. Sieunarine, J. Cox, A. D. Lawson, L. Ungar, and J. R. Smith, "Pulse oximetry and perfusion index measurement to assess uterine perfusion and viability". Int Surg, 91, 223-227. (2006).
[4] N. T. Clancy, D. Stoyanov, V. Sauvage, D. R. C. James, G.-Z. Yang, and D. S. Elson, *A Triple Endoscope System for Alignment of Multispectral Images of Moving Tissue*, in *Biomedical Optics, OSA Technical Digest (CD)*. 2010, Optical Society of America: p. BTuD27.
[5] K. Zuzak, M. D. Schaeberle, E. N. Lewis, and I. W. Levin, "Visible reflectance hyperspectral imaging: characterization of a noninvasive, in vivo system, for determining tissue perfusion". Anal Chem, 74, 2021-2028. (2002).
[6] C. R. Tracy, J. D. Terrell, R. P. Francis, E. F. Wehner, J. Smith, M. Litorja, D. L. Hawkins, M. S. Pearle, J. A. Cadeddu, and K. J. Zuzak, "Characterisation of renal ischemia using DLP hyperspectral imaging: a pilot study comparing artery-only occlusion versus artery and vein occlusion". J Endourol, 24, 321-325. (2010).
[7] S. A. Prahl. *Tabulated molar extinction coefficient for hemoglobin in water*. URL: http://omlc.ogi.edu/spectra/hemoglobin/summary.html.
[8] J. Pilet, V. Lepetit, and P. Fua. "Real-time non-rigid surface detection". in Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition, San Diego, CA, USA 2005) pp. 822-828.
[9] D. Stoyanov and G.-Z. Yang. "Soft tissue deformation for robotic assisted minimally invasive surgery". in Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Minneapolis, MN, USA 2009) pp. 254-257.