Measurement of blood flow in the rotator cuff using laser Doppler flowmetry

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The aim of this study was to define the microcirculation of the normal rotator cuff during arthroscopic surgery and investigate whether it is altered in diseased cuff tissue.

Blood flow was measured intra-operatively by laser Doppler flowmetry. We investigated six different zones of each rotator cuff during the arthroscopic examination of 56 consecutive patients undergoing investigation for impingement, cuff tears or instability; there were 336 measurements overall.

The mean laser Doppler flowmetry flux was significantly higher at the edges of the tear in torn cuffs (43.1, 95% confidence interval (CI) 37.8 to 48.4) compared with normal cuffs (32.8, 95% CI 27.4 to 38.1; p = 0.0089). It was significantly lower across all anatomical locations in cuffs with impingement (25.4, 95% CI 22.4 to 28.5) compared with normal cuffs (p = 0.0196), and significantly lower in cuffs with impingement compared with torn cuffs (p < 0.0001).

Laser Doppler flowmetry analysis of the rotator cuff blood supply indicated a significant difference between the vascularity of the normal and the pathological rotator cuff. We were unable to demonstrate a functional hypoperfusion area or so-called ‘critical zone’ in the normal cuff. The measured flux decreases with advancing impingement, but there is a substantial increase at the edges of rotator cuff tears. This might reflect an attempt at repair.

Degenerative lesions of the rotator cuff are among the most common causes of pain and reduced shoulder function.1-5 Vascular impairment of the supraspinatus tendon leading to microcirculatory disturbances may predispose to such lesions.5 Post-mortem examination by Determe et al6 demonstrated relative hypovascularity near the critical site of degenerative lesions and subsequent ruptures. The microvascular pattern of the diseased cuff was studied in vivo by Biberthaler et al5 using orthogonal polarisation spectral imaging to determine quantitative measurements of the functional capillary density and diameters. However, there are no studies looking at the vascularity of the normal cuff in vivo.

The laser Doppler flowmetry technique measures blood flow in very small blood vessels, such as the low-speed flow in capillaries close to the skin surface and underlying arterioles and venules involved in the regulation of skin temperature.2-6 The thickness of the tissue sampled is typically 1 mm, the capillary diameter 10 μm, and the velocity spectrum 0.01 mm/s to 10 mm/s. This technique is physiological, permits continuous measurement, and is minimally invasive. It adds approximately four minutes to operations involving the rotator cuff.

The technique depends on the Doppler principle, whereby low-power light from a monochromatic stable laser, for example a Helium-Neon gas laser or a single-mode laser diode, is scattered by moving red blood cells, and as a consequence, is frequently broadened. This light, together with laser light scattered from static tissue, is photodetected and the resulting photocurrent processed to provide a measurement of blood flow. Where laser light is scattered in tissue with a low concentration of red blood cells, the average Doppler frequency shift is proportional to the average speed of red blood cells.

The Moor Instruments moorLAB laser Doppler monitor (Moor Instruments Ltd., Millway, Devon) uses laser radiation generated by a semiconductor laser diode operating at a wavelength of 780 ± 10 nm and a maximum accessible power of 1.6 mW. The laser light is coupled into an optical fibre within which it is transmitted to the skin or other tissue. Light is emitted as a diverging beam from the optical probe. The power output from this laser aperture is typi-
cally 0.5 mW to 1.5 mW, with an angular spread of approximately 26°. The flux, an arbitrary unit of measurement of perfusion, is related to the product of the average speed and concentration of moving red blood cells in the tissue sample volume. It is proportional to the blood flow, and is the parameter most widely reported in laser Doppler publications.

The aims of our study were to clarify the value of this instrument for quantitative analysis of the microcirculation of patients during arthroscopic procedures, to determine the pattern of flux in the normal rotator cuffs and to investigate alterations in the microcirculation adjacent to degenerative lesions compared with that of an unaffected control group.

**Patients and Methods**

This prospective study was performed after approval by the local ethics committee, and written informed consent was obtained from all participants. A total of 56 patients (35 men and 21 women) undergoing arthroscopy for impingement (32), cuff tear (diseased cuff, 14) or shoulder instability (normal cuff, 10) were enrolled (Table I). The latter ten patients represented a control group. The mean age was 49.6 years (20 to 75). Traumatic and large/massive tears of the cuff were excluded. This study was carried out in accordance with the World Medical Association Declaration of Helsinki, last amended by the World Medical Association in Edinburgh in 2000.

The patients were anaesthetised using a laryngeal mask and general anaesthesia. No local or regional blocks were used. The patients lay in the lateral position with the arm abducted to 30°. Traction of 6 lb was applied only after measurements were taken. Arthroscopy was undertaken through a standard posterior portal. A pressure- and flow-controlled pump (FMS Duo, Nice, France) allowed saline irrigation without any vasoactive drugs. An additional portal was placed approximately 3 cm lateral to the anterior edge of the acromion in line with the anterior border of the clavicle.

Following diagnostic bursoscopy, the diseased cuffs were subgrouped into mild (B1), moderate (B2), and severe (B3 cuff tear) grades of impingement according to the Copeland-Levy classification. The arthroscopy, grading and placement of the probe were undertaken by one of the two senior authors (SC, OL). The flux was recorded over 30 seconds at each of six points (Fig. 1 and Table II). Five of these were in the cuff over an area of 4 cm² from the insertion at the greater tuberosity.

A MP needle probe (Moor Instruments Ltd, Millway, United Kingdom) (Fig. 2) was used for the measurements. This comprises a hypodermic stainless steel tube of external diameter 0.8 mm and length 80 mm. Separation of the fibre centres (the surface area of light collection by the needle) is 0.25 mm. The probe was inserted using an 18-gauge needle as a conduit through the skin and soft tissues.

The moorLAB laser Doppler monitor (Moor Instruments Ltd) was connected to a personal computer through a USB interface. The computer recorded the flux at each anatomical location for 30 seconds.

**Table I.** Demographic characteristics of the study population

<table>
<thead>
<tr>
<th>Group</th>
<th>Number of cases (%)</th>
<th>Male:Female ratio</th>
<th>Mean age in yrs (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impingement</td>
<td>32 (57.1)</td>
<td>19:13</td>
<td>49.1 (20 to 75)</td>
</tr>
<tr>
<td>Tear</td>
<td>14 (25.0)</td>
<td>7:7</td>
<td>64.2 (43 to 75)</td>
</tr>
<tr>
<td>Normal</td>
<td>10 (17.9)</td>
<td>9:1</td>
<td>30.4 (20 to 48)</td>
</tr>
<tr>
<td>All cases</td>
<td>56 (100)</td>
<td>35:21</td>
<td>49.6 (20 to 75)</td>
</tr>
</tbody>
</table>

**Table II.** Anatomical points where blood flow was measured using the laser Doppler flowmetry probe

<table>
<thead>
<tr>
<th>Point of measurement</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Anterolateral cuff, at greater tuberosity level</td>
</tr>
<tr>
<td>B</td>
<td>Anterior midpoint</td>
</tr>
<tr>
<td>C</td>
<td>Musculotendinous junction</td>
</tr>
<tr>
<td>D</td>
<td>Posterior midpoint</td>
</tr>
<tr>
<td>E</td>
<td>Posterolateral cuff, at greater tuberosity level</td>
</tr>
<tr>
<td>F</td>
<td>Deep (joint side) cuff layers</td>
</tr>
</tbody>
</table>
port for data collection and analysed using a dedicated Window-based package, moorSOFT (Moor Instruments Ltd) for Windows/moorLAB.

During the measurements, the arthroscopic pump was arrested and the valve of the arthroscope opened to ambient air pressure to ensure conditions of physiological pressure within the subacromial space. In order to maintain stable macro-haemodynamic parameters, the mean arterial pressure was controlled by a standard non-invasive pressure device and maintained at 70 mmHg by the anaesthetist throughout the measurement. The CO$_2$ levels were kept below 5.0 kPa. The ambient light effect was eliminated by turning the arthroscopy illumination to a minimum during the readings and confirming that it did not interfere with any measurement. As movement between the tip of the probe and the tissue being measured causes a Doppler shift, thereby producing blood flux artefacts, the surface of the probe was carefully fixed and held to that of the cuff, with the lead secured to prevent unwanted artefact noise. Before each reading, it was confirmed that there was no abnormal blood pooling within the area being measured, as this would have affected measurements of flux.

The values obtained from the cuff disease group were compared with those of the patients with shoulder instability and normal cuffs who also underwent arthroscopic measurements (control group). The outcome variable was the mean flux over a period of 30 seconds. Predictor variables included the patients’ age, gender, the location of measurement (A, B, C, D, E or F, Fig. I and Table II) and the study group (impingement, cuff tear, or normal). Multiple linear regression analysis was carried out to assess how each of these variables might affect the outcome of laser Doppler flowmetry flux, having accounted for all other predictors. The mean measurements of flux in the groups were compared and tested using the t-test and analysis of variance (ANOVA). Statistical analysis was carried out using SAS release 8.2 (SAS Institute Inc., Cary, North Carolina). A value of p < 0.05 was considered significant.

**Results**

In total, 336 measurements were recorded in six anatomical locations in each shoulder. Using multiple linear regression analysis across all 336, with the outcome variable of the flux, and the predictors being age, gender, location and the study group, it was observed that only the study group was a significant predictor of the outcome (F-test, p < 0.0001). Age, gender and anatomical location were not significant predictors of flux (F-test, p = 0.1606, p = 0.2116, p = 3520, respectively).

A highly significant difference in blood flow was observed among the study groups with the mean and 95% confidence interval (CI) for the laser Doppler flowmetry flux as 25.4 (95% CI 22.4 to 28.5) in impingement, 43.1 (95% CI 37.8 to 48.4) with a cuff tear and 32.8 (95% CI 27.4 to 38.1) in the normal cuff (p < 0.0001, one way ANOVA; Table III, Fig. 3).

The normal rotator cuff did not show a clear ‘critical’ zone of hypoperfusion in the lateral (insertional) part of the rotator cuff in this study. In considering 60 readings from the ten control cuffs, there was no statistically significant variation in flux within the six areas measured (t-test, p = 0.2370), and therefore the so-called critical zone of hypoperfusion in the rotator cuff was not demonstrated.

When the samples from the six anatomical locations in the cuff were pooled for analysis, the blood flow was lower in impingement than in normal cuffs (t-test, p = 0.0196). It was higher at the edges of the tear in torn than in normal cuffs (t-test, p = 0.0089), and significantly lower in those with impingement than in those with a tear (t-test, p < 0.0001).

Analysis of the mean laser Doppler flowmetry flux and 95% CI in the normal, impingement and tear groups by anatomical location showed the same trend of reduced blood flow in impingement compared with normal, and an increase in flow at the edges of the tear in torn cuffs compared with the normal cuffs. Statistical significance was achieved only for zones A and E (the anterolateral and posterolateral positions in the cuff at the level of the greater tuberosity level; Fig. 4).

**Discussion**

Laser Doppler flowmetry of the microcirculation has been used in clinical medicine to evaluate and monitor microcirculation in various tissues, including bone.$^{8,11-15}$ In the upper limb, it has been used to assess autonomic dysfunction in frozen shoulders.$^{16}$ It has also been used to measure blood flow in the supraspinatus muscle during isometric contraction,$^{17}$ and for continuous percutaneous measurement of the microcirculation of skeletal muscle at varying levels of force of contraction as determined electromyographically.$^{18}$ However, to our knowledge this is the first study using laser...
Doppler flowmetry to investigate the normal and pathological tendons of the rotator cuff during operation.

The technique has been validated and provides robust data on the microcirculation. Factors affecting the measurements include temperature, external pressure, stress, ambient light and movement artefact. It is important to be aware of these variables so that appropriate precautions can be taken during measurements.

In considering 60 readings from ten control cuffs, there was no statistically significant variation in flux within the six areas measured ($t$-test, $p = 0.2370$), and therefore the so-called critical zone of hypoperfusion in the rotator cuff was not demonstrated. It is questionable whether a larger study might demonstrate a significant difference. The results of our analysis were not borderline as a $p$-value of 0.2370 is far above the significance level of 0.05. Therefore, it is unlikely that there would be significance even in a larger group.

We demonstrated significant differences between the mean flux in normal and diseased cuffs. This was lower in those with impingement than in normal cuffs ($p = 0.0196$) and these preliminary laser Doppler flowmetry recordings agree with the current knowledge of the vascularity of the pathological cuff.$^5,25,27$

The flux was significantly higher at the edges of the tear in torn cuffs than in normals ($p = 0.0089$). This may represent increased vascularity due to a process of repair. We emphasise that massive cuff tears were excluded from the study as we were unable to measure the flux reliably in such cases without dissecting and mobilising the tissue of the cuff, which would have affected the flux. Matthews et al$^{28}$ demonstrated that vascularity and healing potential are reduced in massive tears (grade 4$^{10}$), which were excluded from our study.

We found that the laser Doppler flowmetry flux was significantly lower in cuffs with impingement than in those with tears ($p < 0.0001$). Codman,$^{29}$ on the basis of his cadaver studies and operative findings, described the critical area as the anterior corner of the supraspinatus tendon near its insertion, where it is prone to rupture and is the site of calcium deposits. His work was validated by subsequent cadaver perfusion studies$^{6,24,30-32}$ that demonstrated an area of hypovascularity, and implicated this in the pathogenesis of cuff tears.$^{26,33}$

Brooks et al$^{27}$ performed a quantitative histological study of the vascularity of the rotator cuff tendon. They measured all vessels larger than 20 μm in diameter, irrespective of whether or not they were perfused, and determined

<table>
<thead>
<tr>
<th>Group</th>
<th>Number of measurements</th>
<th>Mean (95% confidence interval)</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impingement</td>
<td>192</td>
<td>25.4 (22.4 to 28.5)</td>
<td>2.2</td>
<td>123.0</td>
</tr>
<tr>
<td>Tear</td>
<td>84</td>
<td>43.1 (37.8 to 48.4)</td>
<td>10.0</td>
<td>114.0</td>
</tr>
<tr>
<td>Normal</td>
<td>60</td>
<td>32.8 (27.4 to 38.1)</td>
<td>7.0</td>
<td>89.1</td>
</tr>
<tr>
<td>Overall</td>
<td>336</td>
<td>31.2 (28.7 to 33.7)</td>
<td>2.2</td>
<td>123.0</td>
</tr>
</tbody>
</table>

Table III. Blood flow (mean laser Doppler flowmetry flux) across all six anatomical locations by cuff disease ($p < 0.0001$, one-way ANOVA)
a reduction in the number and size of the blood vessels between 10 mm and 20 mm from the insertion of supraspinatus. However, they also found an identical vascular critical zone in infraspinatus, which is torn much less frequently.\textsuperscript{34} They questioned the relationship of the critical zone to the aetiology of cuff tears, and concluded that findings based on such studies alone can be misleading.

Conversely, Moseley and Goldie\textsuperscript{35} studied the vascular pattern in the cuff tendons, including the critical zone of the supraspinatus, and found a vascular network that received contributions from the anterior humeral circumflex, subscapular and suprascapular arteries. They concluded that the critical zone was not much less vascularised than other parts of the cuff; rather, it was rich in anastomoses between the osseous and tendinous vessels. Rathbun and Macnab\textsuperscript{36} also studied perfusion both with the arm in full adduction and at 90° of abduction. They noted that the supraspinatus tendon was compressed as it passed over the head of the humerus in adduction, and that its vessels were occluded, whereas they were satisfactorily perfused with the arm abducted. Rothman and Parke\textsuperscript{32} alluded to a similar ‘wringing-out’ effect. Our findings support those of Rathbun and Macnab\textsuperscript{36} and Moseley and Goldie.\textsuperscript{33} The normal tendon has uniform flow and, as measured by laser Doppler flowmetry, there is no significant reduction in functional perfusion in the critical zone. This suggests that reduced vascularity is more likely to be an effect rather than the primary cause of cuff disease.

Swiontkowski et al\textsuperscript{34} performed laser Doppler flowmetry studies on 11 patients during open surgery for rotator cuff disease. They concluded that impingement may produce a hyperaemic response in the cuff, which is contrary to our findings. However, the use of an open approach with detachment of the deltoid may have contributed to their findings, as the surgical trauma may have altered local blood flow. They also noted hyperaemia at the edges of the torn tendon and postulated this as a possible attempt at healing.

Other \textit{in vivo} methods, such as intravital fluorescence microscopy, require the systemic application of potentially toxic\textsuperscript{37,38} fluorescent contrast medium, for example rhodamine-6G and fluorescein isothiocyanate, and a large, expensive intravital microscope. Because of these limitations, \textit{in vivo} studies of microcirculation in humans have been restricted to the skin, nail fold and conjunctiva.

Orthogonal polarisation spectral imaging has been used for quantitative assessment of the human microcirculation in arthroscopic surgery\textsuperscript{36} but this requires the insertion of a 12 mm probe into the subacromial space, which is already compromised in cases of impingement. Also, any quantitative assessment of microcirculatory parameters must be performed from recorded video images. We were unable to demonstrate a functional ‘critical zone of hypoperfusion’ in the normal tendon. This is probably an artefact of the injection technique in cadavers, where most studies have looked at vessels > 20 μm in diameter, whereas laser Doppler flowmetry allows measurements in vessels of 10 μm, which appear to play a significant role in perfusion.

An \textit{in vivo} study carries ethical considerations that introduce inevitable limitations. We were unable to age-match the different groups. Patients were only invited if they required an arthroscopic operation for the treatment of their shoulder, and could not be asked to participate for the purposes of the study alone. The control group comprised patients undergoing arthroscopic evaluation for instability in the absence of abnormal pathology of the cuff. Although this control group is younger, it would be ethically unacceptable to obtain age-matched controls, which would involve recruiting ‘normal’ subjects to undergo an arthroscopic operation.

A major strength of this technique is that it allows real-time output. It could be used in further studies on the rotator cuff, and may help to identify strategies for tendon-repair based on individual patterns of perfusion.

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

References


