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Microvascular blood flow in normal and pathologic rotator cuffs

Shanmugam Karthikeyan, MRCS[a,b], Damian R. Griffin, MPhil, FRCS (Tr & Orth)[a,*], Nicholas Parsons, PhD[a], Thomas M. Lawrence, MD, FRCS (Tr & Orth)[b], Chetan S. Modi, MSc, FRCS (Tr & Orth)[b], Stephen J. Drew, MS, FRCS (Tr & Orth)[b], Christopher D. Smith, MD, FRCS (Tr & Orth)[c]

[a]*Warwick Medical School, University of Warwick, Coventry, UK*
[b]*Department of Trauma and Orthopaedics, University Hospitals Coventry and Warwickshire NHS Trust, Coventry, UK*
[c]*Department of Trauma and Orthopaedics, Royal Devon and Exeter NHS Trust, Exeter, UK*

Background: Microvascular blood flow in the tendon plays an important role in the pathogenesis of rotator cuff abnormalities. There are conflicting views about the presence of a hypovascular zone in the supraspinatus tendon. Besides, no studies have looked at the pattern of blood flow around a partial-thickness tear. Our aim was to measure microvascular blood flow in normal and a range of pathologic rotator cuff tendons using laser doppler flowmetry.
Methods: A total of 120 patients having arthroscopic shoulder surgery were divided into 4 equal groups on the basis of their intraoperative diagnosis: normal rotator cuff, subacromial impingement syndrome, and partial-thickness or full-thickness rotator cuff tear. Microvascular blood flow was measured at 5 different regions of each cuff using a laser doppler probe. The values were compared to assess variability within and between individuals.
Results: Total blood flow was greater in the normal rotator cuff group compared with the groups with pathologic rotator cuffs, with the largest difference seen in the subacromial impingement group. Within individuals, blood flow was highest at the musculotendinous junction and lowest at the lateral insertional part of the tendon. Among groups, the blood flow was significantly lower at the anteromedial and posteromedial cuff in the groups with impingement and full-thickness tears compared with the group with normal cuff.
Conclusion: Real-time in vivo laser doppler analysis has shown that microvascular blood flow is not uniform throughout the supraspinatus tendon. Blood flow in the pathologic supraspinatus tendon was significantly lower compared with the normal tendon.
Level of evidence: Basic Science Study, Anatomy Study, Imaging.

Keywords: Rotator cuff; supraspinatus; blood flow; microvascular; laser doppler flowmetry; impingement; cuff tear; critical zone

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*Reprint requests: Damian R. Griffin, MPhil, FRCS (Tr & Orth), Warwick Medical School, CSRL (1st Floor Clinical Sciences Building), University Hospitals Coventry and Warwickshire NHS Trust, Clifford Bridge Road, Coventry CV2 2DX, UK.
E-mail address: damian.griffin@warwick.ac.uk (D.R. Griffin).

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Rotator cuff disorders are a serious and disabling condition[20,27] and the most common cause of shoulder pain seen by physicians.[15] The condition affects adult patients of all ages[5,29] and is often associated with prolonged periods off work and sporting activities.[2]

Vascular insufficiency has been proposed as one of the causes of rotator cuff disease.[4,19,28,30] According to this theory, reduced blood flow to certain areas of the tendon is associated with microcirculatory disturbances with resultant tendinopathy, poor tendon healing, and ultimately tears in some cases. The principal blood supply to the rotator cuff comes from the suprascapular and anterior and posterior circumflex humeral arteries.[4,19,30] However, since Codman[6] described a watershed area in the rotator cuff, there is debate as to whether there is a "critical area" of relative avascularity in the supraspinatus tendon, just proximal to its bony insertion, that makes it vulnerable to tendinopathy and eventual tears.[8,17-19,22,28,30,34,35]

The presence of a critical zone is primarily supported by in vitro studies.[8,18,19,28,30] Most of these studies involved injecting a hardening substance and analyzing resultant tissues by histologic techniques. This process can create technical problems, such as microemboli, and made the studies inherently weak. Recent studies using in vivo physiologic techniques, such as doppler ultrasound and laser doppler flowmetry (LDF), have failed to support the presence of a critical zone in the rotator cuff.[12,17,34,35] However, these studies were limited by small sample sizes and inefficient analyses. Also, the pattern of blood flow around a partial-thickness tear has not previously been studied as a separate group. The microvascular pattern of the rotator cuff in living subjects therefore remains unclear.

Rotator cuff vascularity plays an important role in the rehabilitation and surgical interventions that are chosen to treat cuff disease.[14] Blood flow in the rotator cuff has been previously measured in vivo using power doppler ultrasound,[9] contrast-enhanced ultrasound,[12] and LDF.[17] LDF has previously provided reliable assessment of human blood flow in the skin,[16] Achilles tendon,[2] and anterior cruciate ligament.[33] A recent review article highlighted the lack of definitive knowledge in this field and concluded that further larger studies were needed using in vivo LDF.[14]

The aim of this study was to test our hypothesis that (1) there is no difference in the microvascular blood flow in patients with normal rotator cuffs compared with patients with pathologic rotator cuffs, including full- and partial-thickness tears, and (2) there is no difference in the microvascular blood flow between different regions of the rotator cuff, by in vivo LDF in a large cohort of patients undergoing arthroscopic shoulder surgery. Blood flow was measured in 5 different regions of the rotator cuff and compared to assess variability between and within individuals.

Materials and methods

Patients

Patients having arthroscopic shoulder surgery under the care of 2 shoulder surgeons (S.J.D. and T.M.L.) formed the study population. Study participants were categorized into 4 groups on the basis of their intraoperative diagnosis:

1. Normal rotator cuff and undergoing surgery for unrelated disease (stabilization and labral repairs) (control group)
2. Subacromial impingement syndrome
3. Partial-thickness rotator cuff tears
4. Full-thickness rotator cuff tears

All patients presented with shoulder pain related to the rotator cuff (except the control group). All patients had symptoms for a minimum of 3 months and previously had a course of conservative management including analgesia, physiotherapy, and subacromial injection where appropriate. Diagnosis of impingement was made by an experienced consultant shoulder surgeon in patients who had a painful arc and positive impingement signs but with no radiologic or intraoperative evidence of a cuff tear. There were no acute traumatic cuff tears. Measurements were taken from 30 consecutive patients in each group, giving a total of 120 patients for the study.

Inclusion criteria

All adult patients presenting at our institution who were able to give informed consent and having arthroscopic shoulder surgery under the care of 2 consultant orthopedic surgeons (S.J.D., T.M.L.) for full-thickness rotator cuff tears, partial-thickness rotator cuff tears, subacromial impingement, labral repair, or stabilization procedures were considered eligible for the study. Patients were older than 18 years, had not undergone previous shoulder surgery, and had no comorbidities that may affect microvascular blood flow (e.g., patients with diabetes, inflammatory arthritis, synovitis, or adhesive capsulitis). In the group with full-thickness tears, only patients with tears up to 2 cm were included. Patients with traumatic, large, or massive cuff tears were excluded.

Equipment

The moorVMS-LDF laser doppler blood flow monitor (Moor Instruments Ltd., Axminster, Devon, UK) is a high-performance medical-grade instrument for clinical and research applications.[17] It uses a semiconductor laser diode to generate laser radiation with a wavelength of 785 ± 10 nm and a maximum power output of 2.5 mW. This low-power laser light is transmitted through an optic fiber to a VP3 needle probe (Moor Instruments Ltd.), which has an external diameter of 1.5 mm and length of 80 mm. The probe was calibrated regularly using a motility standard supplied by the manufacturer.

LDF is based on the principle that an estimate of the blood perfusion can be achieved by illuminating a tissue sample with single-frequency light and processing the frequency distribution of the backscattered light.[10] When the probe is placed on the rotator cuff, the light from the tip of the needle is scattered by tissue and moving blood cells and its frequency altered. A photodetector collects the scattered light, and the resulting current is electronically processed to give an output, measured in flux units.

Methods

All operations were performed in the beach chair position under general anesthesia with an interscalene nerve block. No traction was applied. A saline irrigation pump was used throughout the procedure. The LDF technique is similar to the one described by Levy et al.[17] Each patient had a full arthroscopic assessment through standard arthroscopic portals. Following diagnostic arthroscopy, a VP3 laser doppler probe was introduced either through an existing lateral portal or by use of a 16-gauge needle as a conduit through the skin into the subacromial space to measure the microvascular blood flow in 5 different regions of the bursal side of the rotator cuff under standard conditions. The regions were anterolateral and posterolateral (at its insertion), anteromedial and posteromedial (1 cm medial to insertion), and musculotendinous junction (Fig. 1). No measurements were taken from the deep (articular) surface of the cuff. For the group with full-thickness tears, the anterolateral and posterolateral measurements were taken at the medial edges of the tear. The anteromedial and posteromedial measurements were taken 1 cm medial from the edge of the tear.

To eliminate artifacts during the measurement, the intensity of the arthroscopic light source was turned to minimum and the saline irrigation pump was stopped to ensure normal physiologic pressure in the subacromial space. Care was taken to avoid pooling of blood at the measurement site, and the lead was secured to minimize any movement. The mean arterial pressure was maintained between 70 and 80 mm Hg throughout the measurements. Output was measured as "flux," which is proportional to the speed and concentration of red blood cells in the tissue.

Statistical analysis

Data were summarized by calculating means and standard deviations and presented graphically using box and scatter plots. Exploratory linear regression analysis was used to quantify the relationship between age and blood flow, and *t* tests and χ^2 tests were used to assess differences between study groups.

An adjusted stratified analysis of variance (ANOVA) procedure was used to assess differences in blood flow between zones (1, anterolateral; 2, posterolateral; 3, anteromedial; 4, posteromedial; and 5, musculotendinous) within individuals and between groups of individuals (normal, impingement, partial tear, and full tear). The 2 strata identified in the analysis were associated with comparisons between individuals (diagnosis groups) and within individuals (zones). Analyses were such that effects for both groups and zones were partitioned into single degree of freedom contrasts that allowed assessment of each hypothesis; for example, for groups, this meant that the 3 degrees of freedom for comparing groups were split into single contrasts reporting (1) normal vs. impingement, (2) normal vs. partial tear, and (3) normal vs. full tear. *F* tests were used to assess statistical significance, which was set at the 5% level. Data were analyzed after logarithmic transformation to improve the normality assumptions required for ANOVA and linear regression.

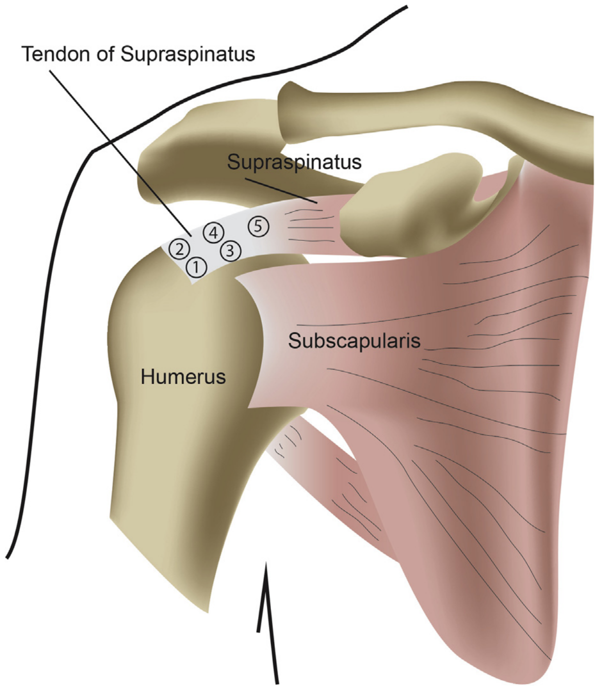

Figure 1 Blood flow measurement zones on the rotator cuff: *1*, anterolateral; *2*, posterolateral; *3*, anteromedial; *4*, posteromedial; and *5*, musculotendinous.

Results

The demographics of the study population are shown in Table I. The group with the normal rotator cuff was predominantly male (χ^2 test; $P = .008$) and significantly younger than the other groups (*t* test; $P < .001$). However, a linear regression analysis of the relationship between blood flow and age within study groups (normal and other groups) showed that regression coefficients were zero, indicating that there was no evidence for an association between age and blood flow within any of the groups (Fig. 2). There was no evidence that blood flow differed between genders (*t* test; $P = .858$).

Of the 30 patients with partial-thickness tears, 27 had articular-sided partial-thickness tears and 3 had bursal-sided partial-thickness tears.

The ANOVA indicated that the total blood flow measured across all regions was greater in the normal rotator cuff group compared with the groups with pathologic rotator cuffs (ANOVA *F* test; $P = .001$) (Fig. 3), with the largest difference seen in the subacromial impingement group ($P = .008$).

There were significant differences in blood flow between the 5 zones (Figs. 1 and 3). Blood flow was highest at the musculotendinous junction (zone 5) compared with the blood flow in the tendinous part (zones 1-4). This difference was highly significant (ANOVA *F* test; $P < .001$) and was observed consistently across all 4 groups. Analysis of measurements in zones 1 to 4 across all 4 groups indicated

Table I Demographics of study population

Criterion	Normal	Impingement	Partial tear	Full tear
Age				
Mean (SD)	30 (7.8)	55 (10.3)	57 (13.1)	63 (10.1)
(Range)	(18-48)	(35-78)	(26-80)	(45-88)
Sex				
Male:female	24:6	14:16	19:11	12:18

Age is expressed in years as mean with standard deviation (SD) and range. Sex distribution is expressed as a ratio.

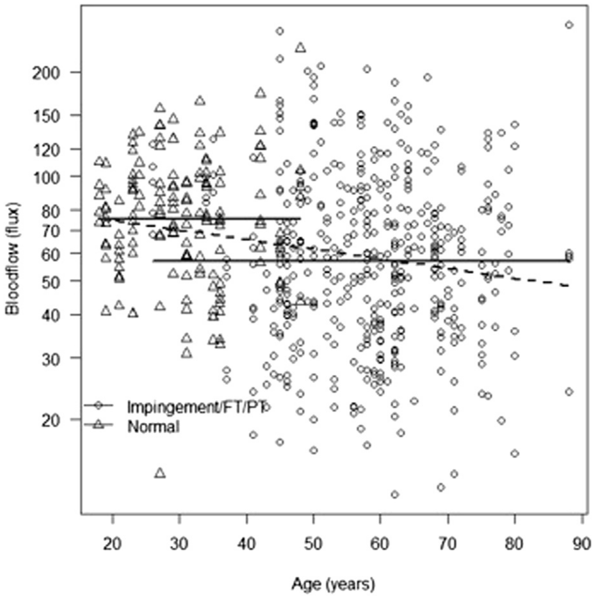

Figure 2 Scatter plot of blood flow vs. participant age for normal and non-normal groups. A linear regression ignoring groups (- -) showed a significant negative association between age and blood flow ($P < .001$). However, adding an interaction term to this model ($P = .003$) showed that the association was purely between groups, as the regression coefficients within groups were zero (—). *FT*, full tear; *PT*, partial tear.

that blood flow in the lateral insertional part of the tendon (zones 1 and 2) was significantly lower ($P = .002$) than in the medial part (zones 3 and 4). It also indicated that the pattern of blood flow between zones was almost equivalent for normal, partial-tear, and impingement groups but different for the full-tear group ($P = .020$). In the full-tear group, we saw no great differences between zone 1, zone 2, zone 3, and zone 4, although all were much lower than in zone 5.

Analysis of the blood flow at individual zones between the groups has shown that the blood flow was significantly lower at the anteromedial and posteromedial cuff (zones 3 and 4) in the group with impingement (ANOVA F tests; zone 3, $P = .010$ and zone 4, $P = .028$) and full-thickness tears (zone 3, $P = .015$ and zone 4, $P = .042$) compared

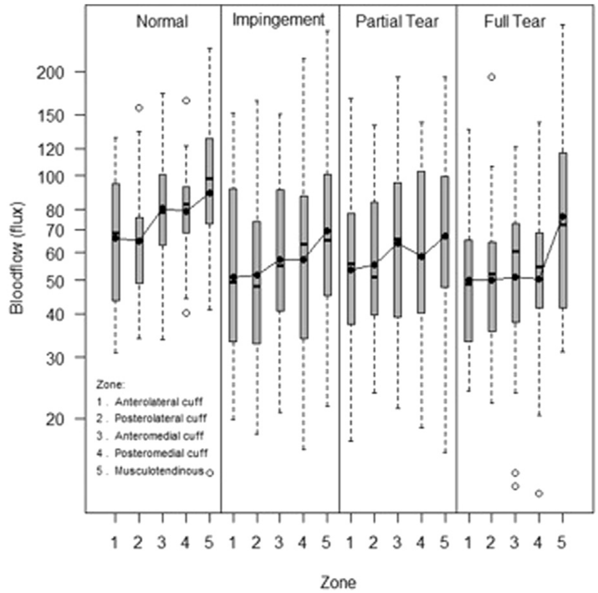

Figure 3 Box plots for each group and zone, with means (●); the vertical axis is plotted on a log scale, as this was used for the analysis to improve normality assumptions.

with the group with normal cuff. This difference at zones 3 and 4 did not reach statistical significance in the group with partial-thickness tears (zone 3, $P = .562$ and zone 4, $P = .273$).

Discussion

In our study, the cumulative blood flow measured across all regions was highest in the group with the normal rotator cuff. The total blood flow was lower in all the groups with a pathologic rotator cuff (subacromial impingement, partial-thickness tear, and full-thickness tear), with the lowest values in the group with impingement (Table II). We are aware that the group with the normal rotator cuff was significantly younger compared with the pathologic group. Although Rudzki et al[31] and Funakoshi et al[12] have shown an age-related decrease in intratendinous vascularity of the supraspinatus using contrast-enhanced ultrasound, our data showed no strong evidence that blood flow decreased significantly with age. Our results are similar to those of Levy et al,[17] who also used LDF and found that the total blood flow was significantly lower in the group with impingement and that age and gender were not significant predictors of blood flow in the tendon.

Our results also demonstrate that the blood flow is not uniform throughout the tendon. The blood flow is highest medially at the musculotendinous junction and is lower laterally, with the lowest values seen at the point of insertion of the tendon onto the bone (Table II). Within the control group, blood flow was significantly higher at the musculotendinous junction (zone 5) compared with the medial part of the tendon (zones 3 and 4), which in turn was significantly

Table II Mean flux values (with 95% confidence intervals) for the 4 groups at each region

Region	Group			
	Normal	Impingement	Partial tear	Full tear
Anterolateral	71.61 (61.24-81.99)	61.02 (46.71-75.34)	61.35 (48.85-73.85)	56.99 (45.06-68.92)
Posterolateral	69.23 (58.63-79.82)	61.74 (46.91-76.57)	62.01 (50.37-73.65)	56.40 (44.09-68.70)
Anteromedial	85.83 (74.35-97.32)	64.93 (52.83-77.03)	74.93 (58.91-90.96)	57.69 (48.20-67.18)
Posteromedial	82.31 (73.06-91.56)	72.67 (53.28-92.05)	67.56 (54.24-80.87)	58.62 (46.87-70.38)
Musculotendinous	99.71 (83.66-115.76)	81.85 (62.42-101.28)	77.72 (62.20-93.23)	92.29 (69.14-115.43)
Mean	81.74 (76.41-87.07)	68.44 (61.39-75.5)	68.71 (62.69-74.74)	64.40 (57.8-71.0)

higher than the lateral part of the tendon (zones 1 and 2). These results would be expected in any muscle-tendon-bone transition, with the muscle having the most vascularity and decreasing as the tissue becomes more tendinous.[2] It does not support a critical zone of avascularity in the midsubstance of the tendon. Many histologic studies have described a markedly hypovascular area compared with the rest of the tendon in the distal part of the supraspinatus tendon just proximal to its insertion.[19,28,30] Moseley and Goldie[22] have shown that the critical zone corresponds to the zone of the anastomoses between the osseous and the tendinous vessels but found no evidence that it is much less vascularized than any other part of the tendinous cuff. However, all these injection techniques have an inherent weakness in that injected suspensions of any material always form emboli at the capillary level of the vascular bed, as acknowledged by Rathbun and Macnab.[28] Recently, contrast-enhanced ultrasound has been used to study blood flow in the rotator cuff. Adler et al[1] found regional variations in the intratendinous blood flow with the lowest values at the articular medial margin of the rotator cuff, whereas Funakoshi et al[12] did not find any significant difference in the vascular distribution within the supraspinatus tendon. Using LDF, Levy et al[17] were unable to find a critical zone in the supraspinatus tendon. Similar results were seen in the Achilles tendon, where LDF has shown that blood flow is lower near tendon insertion.[2]

Across the groups, the difference in blood flow was pronounced mainly in the medial part of the tendon (zones 3 and 4), where it was significantly lower in the groups with impingement and full-thickness tears compared with the normal group. This difference was not significant in the partial-thickness tear group. Hypervascularity at the edge of partial-thickness tears was noted by Fukuda et al[11] on histology and Swiontkowski et al[35] by LDF. Matthews et al[21] have shown increased blood vessel proliferation and fibroblast cellularity in small rotator cuff tears, but as the tear size increased, there was a trend toward reduced vascularity. Although Levy et al[17] have shown higher blood flows in all regions on the bursal surface for the group with cuff tears compared with normal cuffs, in our study we did not see this response. In our study, we have split the cuff tears group into full- and partial-thickness tears to define whether there is a difference between these 2 subgroups. We have also defined exactly where measurements are taken in relation to the tear. These 2 factors may account for the differences in the results from the 2 studies.

Although both extrinsic and intrinsic theories have been proposed as the possible etiology of rotator cuff tears,[3,23,24] most authors currently believe that intrinsic tendon degeneration probably linked to microvascular disturbances predominates.[7,13,25,32] Thus, enhancing knowledge regarding the microvascular blood flow of the rotator cuff is essential in further understanding the pathologic processes. Whereas some anatomic studies have shown a consistent crossover of blood vessels across the osteotendinous junction in supraspinatus,[26] others have shown that almost no vessels are present distally at the articular surface of the tendon.[19] Most cadaveric studies[19,28,30] have documented the poor microvascular supply within the supraspinatus tendon, but in vivo measurements have contradicted these findings with an increase in blood flow on the edge of a full-thickness tear.[12,17,34,35]

This is the first study to directly compare the microvascular blood flow in partial-thickness tears and adds to previous work on the microvasculature in normal and fully torn rotator cuffs.[17] This is a physiologic in vivo technique that allowed real-time measurement of blood flow. We were also able to demonstrate variability in the rotator cuff blood flow within individuals and across different groups. The main limitation was our inability to age match the groups. Ethical considerations for an in vivo study meant the control group with normal rotator cuffs could comprise only patients who were having arthroscopic surgery for an alternative diagnosis with no obvious disease of the rotator cuff. This group therefore had patients mainly undergoing stabilization surgery who were younger and predominantly male. The other limiting factor is that currently, LDF does not provide an absolute measure of blood perfusion, therefore making it difficult to make a direct comparison of values obtained by other methods, but it did allow comparison between the groups in our study.

This study adds to that of Levy et al[17] that the impinged cuff has a reduced blood flow compared with a normal cuff. It also demonstrates that the torn cuff has an increased blood flow in comparison to the impinged cuff and there is no significant difference between the partial- and full-thickness cuff tear groups. This could be postulated that the impinged cuff is at risk of tear due to a decreased blood flow phenomenon and that the torn cuff responds with an increase in blood flow.

Conclusion

Real-time in vivo laser Doppler analysis has shown that the microvascularity of rotator cuff is not uniform throughout the tendon. There are regional variations, with the lowest blood flow found at the point of insertion of the tendon, suggesting that a critical zone of hypovascularity medial to its insertion may not exist. The total blood flow in the supraspinatus tendon was found to be significantly lower in the pathologic tendon compared with the normal tendon, with the lowest values seen in patients with impingement.

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Disclaimer

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