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Limb perfusion in the lower limb amputee— a comparative study using a laser Doppler flowmeter and a transcutaneous oxygen electrode

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Abstract

Accurate and objective assessment of amputation level in the lower limb plays an important role in patient management. Laser Doppler flowmetry (LDF) is a new and non-invasive technique for skin blood flow measurement and has been used pre-operatively in 25 patients undergoing amputation for vascular disease and in five normal controls. Baseline flux measurements were made at room temperature on the medial aspect of legs and then again after local heating of the skin for five minutes. Transcutaneous oxygen measurements were made at the same site for comparison and amputation level in patients selected on this basis.

Significant differences ($p<0.001$) in $TcPO_2$ values were found between controls (10.9 ± 0.5kPa), below-knee (BK) amputees (6.0 ± 1.5kPa) and above-knee (AK) amputees (1.5 ± 0.6kPa). Baseline LDF flux did not differ significantly between any group. Heated flux values did however show a significant difference ($p<0.005$) between controls (52.4 ± 23.5) and both BK (20.6 ± 9.2) and AK groups (8.1 ± 7.7) and also between the amputee groups. The relative increase in flux (heated flux/baseline flux) differed significantly between the BK (3.3 ± 1.5) and AK (1.2 ± 0.3) groups ($p<0.001$) and between these two and the controls (11.2 ± 5.4) ($p<0.001$). The correlation between relative increase in flux and $TcPO_2$ was 0.7 ($p<0.001$).

It is concluded that laser Doppler flowmetry used in conjunction with thermal stressing could provide a quick, simple and non-invasive method for objectively determining amputation level in the lower limb.

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Introduction

In spite of advances in vascular surgery over the last decade, patients with degenerative vascular disease are still coming to major amputation when reconstruction is no longer feasible. In 1984, 85% of all new patients referred to the Artificial Limb and Appliance Centres (ALAC) in England and Wales suffered from vascular disease or diabetes and 78% were over 60 years of age (HMSO, 1985). In a society with an ageing population it is important that each amputation heals primarily, with preservation of the knee joint (Robinson, 1976) giving the patient the greater chance of successful rehabilitation on a prosthesis. Accurate assessment of amputation level is therefore of considerable importance in the management of the patient.

Clinical evaluation of the limb has been the standard way in which amputation level has been selected but it is highly subjective. Objective methods for the determination of amputation level that have been widely used in the last few years include clearance of radioisotopes (Malone et al, 1981) and transcutaneous oxygen measurements (Burgess et al, 1982). The former technique is often regarded as the "gold standard" because it provides a quantitative measure of skin blood flow, whereas the adequacy of the blood supply is only implied by measurement of percutaneous oxygen tension.

Laser Doppler flowmetry is a relatively new and non-invasive technique for measuring blood flow in the microcirculation of the skin (Nilsson et al, 1980). Doppler shifts in laser light produced by moving red blood cells are detected and electronically processed to provide a measure of blood flow, termed flux. This flux is the product of the concentration of cells in the measurement volume and their average velocity. Since the penetration depth of

helium-neon laser light in the skin is of the order of 0.6mm only flow in the microcirculation is detected (Anderson and Parrish, 1981).

Radioisotope clearance and transcutaneous oxygen measurements are both time consuming and somewhat complex methods of determining skin blood flow. Laser Doppler flowmetry would appear to offer a quick and simpler alternative. The authors have accordingly attempted to evaluate this new instrument by comparing its use alongside transcutaneous oxygen measurements made in a group of patients proceeding to lower limb amputation and in a group of normal control subjects.

Patients and methods

Transcutaneous oxygen measurement ($TcPO_2$) and laser Doppler flowmeter (LDF) flux values were obtained pre-operatively on 25 patients undergoing lower limb amputation for vascular disease and from five healthy subjects with no evidence of vascular disease.

All measurements were made with the subject in a semi-recumbent position after allowing at least 15 minutes for them to equilibrate. Sites on the medial aspect of both legs, 13cm from the knee joint line and 5cm from the tibia were used for both instruments. A measurement at a lateral site, 13cm from the knee joint and 3cm from the tibia was also made with the LDF. Both LDF and $TcPO_2$ measurements were made sequentially on identical sites. Baseline flux values at room temperature were first obtained from the LDF, (Periflux PFId) followed by readings made after 5 minutes local heating of the skin at 42°C (the maximum possible using the instruments integrated heating element). A time constant of 3 secs was selected on the LDF and a frequency cut off of 4kHz, settings which are optimum for obtaining mean, rather than pulsatile readings. The more slowly varying mean flow is easier to interpret, unlike the pulsatile signal which exhibits a "hunting phenomenon" in critically ischaemic skin. This phenomenon is variable between patients and difficult to quantify.

The LDF evaluation was followed by a $TcPO_2$ measurement (Roche $TcPO_2$ monitor 632) in which the heating element temperature was set at 45°C, the temperature at which previous work in determining critical levels for amputation with the $TcPO_2$ has been done. Measurements of $TcPO_2$ were made when the temporal variations in measured level were within 0.1kPa. This usually occurred about 15 minutes after placement of the electrode on the skin. Amputation levels were selected by the referring clinician on the basis of the $TcPO_2$ readings using pre-determined levels (Butler, 1985). A transcutaneous oxygen tension of less than 2.7kPa is taken as indicating above-knee amputation. By following the LDF measurements by the $TcPO_2$ estimations the procedure overcomes the possible errors caused by heating to 45°C just prior to heating to 42°.

$TcPO_2$ measurements, LDF baseline and heated flux values were expressed as mean ± standard deviation. The relative increase in LDF flux produced by heating was calculated (heated flux/baseline flux) and was similarly expressed.

Apparent differences in the mean values of all measured and derived parameters, between the controls, BK amputees and AK amputees were analysed for statistical significance using the Student's t-test for unpaired data.

Results

All amputations performed in this small series healed primarily at the level chosen. Transcutaneous oxygen and LDF values for each group are presented in Table 1. Significant differences exist ($p<0.001$) between the $TcPO_2$ measurements of each group (This would be expected since the amputation level was largely

Table 1. LDF flux and $TcPO_2$ values measured on medial and lateral aspects of the legs of controls (C), BK amputees and AK amputees. Mean values are given ± one standard deviation.

	Medial Site			Lateral Site		
Variable	C	BK	AK	C	BK	AK
Number	5	14	11	5	13	10
Baseline flux	5.4± 1.5	6.9±3.6	7.0±6.3	5.8± 2.9	6.4± 4.4	5.0±3.4
Heated flux	52.4±23.5	20.6±9.2	8.1± 7.7	47.3±12.3	22.8±15.8	5.5±3.6
Relative increase in flux	11.2± 5.4	3.3±1.5	1.2± 0.3	9.9± 4.9	4.5± 4.2	1.2±0.3
$TcPO_2$, kPa	10.9± 0.5	6.0±1.5	1.5± 0.6	—	—	—

determined on the basis of this measurement).

The baseline LDF flux values for the controls, BK and AK patients were not found to differ significantly. However, a significant difference existed between the heated flux of the control and both the BK and AK groups ($p<0.001$). The difference between the heated flux of both amputee groups was also significant ($p<0.005$).

A more significant difference between the BK and AK group was found when the relative increase in flux was considered ($p<0.001$). The difference between the controls and BK or AK groups using this parameter was also significant ($p<0.001$). Figure 1 illustrates the correlation between $TcPO_2$ and the relative increase in LDF flux ($r=0.7$, $p<0.001$).

Discussion

Laser Doppler flowmetry is a recent addition to the range of techniques available for microcirculatory measurements. It has been previously used in assessing skin flap viability (Jones and Mayou, 1982), muscle blood flow (Oberg et al, 1979) and the evaluation of peripheral vascular disease (Karanfilian, 1984). Good agreement between standard skin blood flow measurement techniques and laser Doppler flux has been demonstrated (Watkins and Holloway, 1978; Stern et al, 1977). Although LDF cannot provide a quantitative measure of skin blood flow, comparisions of flux values are possible enabling stimulus/response type experiments to be performed.

As would be expected, skin oxygen levels are related to blood flow (LDF flux). Figure 1 shows that $TcPO_2$ rises asymptotically towards the normal levels which for patients over 60 is typically 10.6 kPa (the 95% range extending from 8.32 to 12.84 kPa). Figure 1 shows the correlation between relative increase in flux on heating as a function of $TcPO_2$ and demonstrates how sensitive $TcPO_2$ levels are to relatively small changes in vascular reactivity. Relative flux was plotted rather than absolute flux as the authors' experience in monitoring reconstructed vascular surgery has indicated that vascular reactivity is likely to be a better indicator of potential for healing than absolute flow level. In fact the correlations are very similar though marginally poorer for the absolute heated flux/$TcPO_2$ characteristic.

Support for this approach comes from the

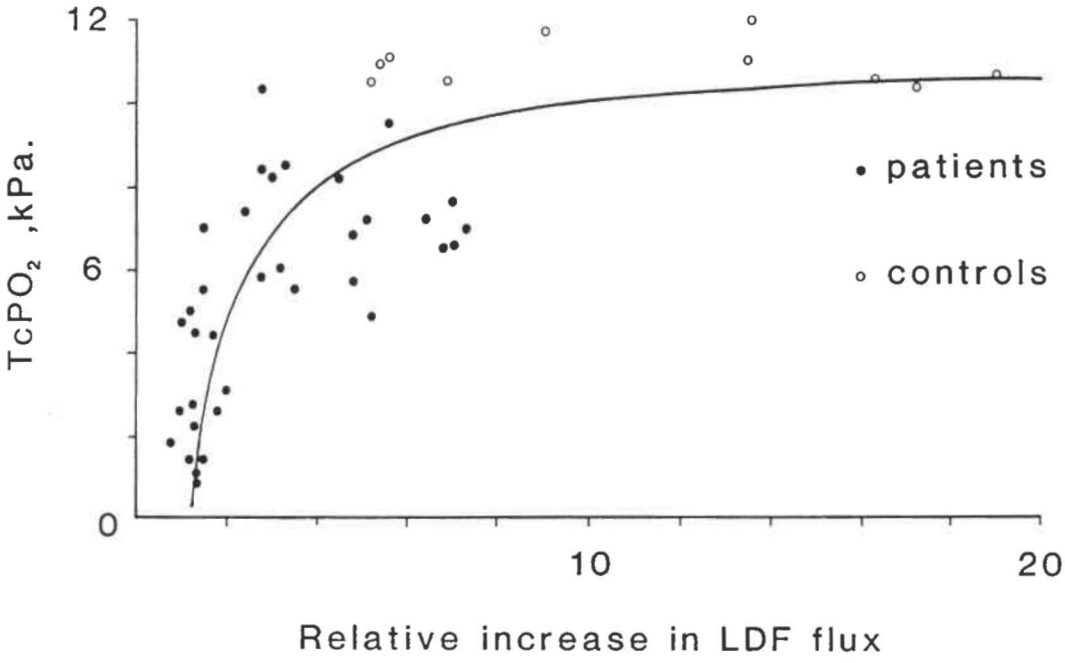

Fig. 1. Plot showing the results of relative increase in blood flow flux following heating as a function of skin $TcPO_2$ in kPa. The open circles represent normal subjects, the closed circles the amputee patients.

results of the present study which show that baseline LDF values which are in fact a measure of resting blood flow, do not permit discrimination between controls and patients. A similar observation has been made in patients and controls on the lateral aspect of the leg which would agree with the authors' findings (Pabst et al, 1985).

After local heating of the skin, the flux values recorded allowed the control group to be distinguished from patients with vascular disease and separation of BK/AK groups was possible. By considering the relative increase in flux (heated flux/baseline flux) it was also possible to separate BK amputations from AK, and both of these from the controls. The latter parameter is considered to be of most use in discriminating between the BK and AK groups because it is not influenced by the actual LDF value after heating but is a measure of microcirculatory reactivity.

In a previously reported uncontrolled pilot study using an LDF for amputation level selection, the increase in flux brought about by local heating was also measured (Holloway and Burgess, 1983). Although no exact values are given, successful amputation in both AK and BK patients was indicated when the flux achieved after heating was at least one third of that seen in controls. The findings in the present study differ substantially in that all AK amputations were found to heal primarily in situations where the heated flux was less than 30% of the control levels. However, exact comparisons are difficult because of the paucity of information in the previously published work.

A study of LDF in controls and patients with peripheral vascular disease (PVD) has shown that a significant difference in baseline level exists between controls and severely ischaemic limbs in the great toe only (Pabst et al, 1985). Differences were not found at more proximal sites between controls and either mild or severe PVD, a finding which the authors' observations confirm. The derivation of a reactive hyperaemic index in these groups showed a significant difference between the control and severe PVD groups at all sites on the limb. However, a distinction between mild and severe ischaemia could not be made at any site on the leg, an indication that the technique would probably be of little value in assessing amputation level. In any event, producing reactive hyperaemia in patients with severe ischaemia is questionable in terms of the pain it produces. In the authors' experience, pre-operative pain in the amputation patient is not always well controlled. These patients are often acute admissions in need of immediate amputation surgery, or their condition has deteriorated rapidly following other unsuccessful vascular prodecures. Therefore any technique which could painlessly obtain the same information would be preferable.

It might be argued that the scatter of the points in this limited series of observations suggests that there is only a poor correlation between skin oxygen levels and flux change. However, a one-to-one correlation would not be expected. Indeed, since healing is as likely (if not more so) to be influenced by tissue perfusion rather than skin oxygen the results suggest that laser Doppler flowmetry could be equally effective in determining amputation level. From these present results, local heating of the skin and evaluation of its response to this stimulus with an LDF would appear to be a more sensitive (and certainly painless) test for determining the degree of ischaemia in the lower limb and hence the most distal level for successful amputation.

The authors' experience over several years in measuring $TcPO_2$ levels in amputees suggests that the technique demands meticulous and time consuming attention to detail and system recalibration, even when moving the instrument between two patients on the same ward. More recent experience with the LDF has shown it, for the most part, to be far more reliable, simpler and quicker to use and intrinsically more stable. However, on a number of occasions some instability has been noted in the readings indicated. This instability appears to be a function of movement of the fibreoptic bundle and is related to the multimode nature of the fibres (Moore, 1985). The artefact can be overcome by stabilizing the fibre bundle, by taping it to the bed clothes for example.

Despite this reservation it is believed that the LDF in conjunction with thermal stressing of the skin could provide the best method available for determining the level for lower limb amputation. Its use now needs evaluation in a controlled prospective trial.

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REFERENCES

ANDERSON, R. R., PARRISH, J. A. (1981). The optics of human skin. *J. Invest. Dermatol.* **77,** 13–19.

BURGESS, E. M., MATSEN, F. A., WYSS, C. R., SIMONS, C. W. (1982). Segmental transcutaneous measurements of PO_2 in patients requiring below-the-knee amputation for peripheral vascular insufficiency. *J. Bone Joint Surg.* **64A,** 378–382.

BUTLER, C. M. (1985). The vascular amputee. M. S. Thesis, University of London.

DHSS (1985). On the state of the Public Health for the year 1984: HMSO.

HOLLOWAY, G. A. JR., BURGESS, E. M. (1983). Preliminary experiences with laser Doppler velocimetry for the determination of amputation levels. *Prosthet. Orthot. Int.* **7,** 63–66.

JONES, B. M., MAYOU, B. J (1982). The laser Doppler flowmeter for microvascular monitoring: a preliminary report. *Brit. J. Plast. Surg.* **35,** 147–149.

KARANFILIAN, R. G., LYNCH, T. G., LEE, B. C., LONG, J. B., HOBSON, R. W. (1984). The assessment of skin blood flow in peripheral vascular disease by laser Doppler velocimetry. *Am. Surg.* **50,** 641–644.

MALONE, J. M., LEAL, J. M., MOORE, W. S., HENRY, R. E., DALY, M. J., PATTON, M. D., CHILDERS, S. J. (1981). The "gold standard" for amputation level selection: Xe–133 clearance. *J. Surg. Res.* **30,** 449–455.

MOORE, G. (1985). Single-frequency lasers: a light at the end of the tunnel. *Electronics and Power:* 373–376.

NILSSON, G. E., TENLAND T., OBERG, P. A. (1980). Evaluation of a laser Doppler flowmeter for measurement of tissue blood flow. IEEE Trans. Biomed. Eng, **27,** 597–604.

OBERG, P. A., NILSSON, P. A., TENLAND, T., HOLMSTROM, A., LEWIS, D. H. (1979). Use of a new laser Doppler flowmeter for measurement of capillary blood flow in skeletal muscle after bullet wounding. *Acta. Chir. Scand. (suppl.)* **489,** 145–150.

PABST, T. S., III., CASTRONUOVO, J. J. JR., JACKSON, S. D., SCHULER, J. J., FLANAGAN, D. P. (1985). Evaluation of the ischemic limb by pressure and flow measurements of the skin microcirculation as determined by laser Doppler velocimetry. *Curr. Surg.* **42,** 29–31.

ROBINSON, K. P. (1976). Long posterior flap amputation in geriatric patients with ischaemic disease. *Ann. R. Coll. Surg. Engl.* **58,** 440–451.

STERN, M. D., LAPPE, D. L., BOWEN, P. D., ET AL (1977). Continuous measurement of tissue blood flow by laser Doppler spectroscopy. *Am. J. Physiol* **232,** H441–H448.

WATKINGS, D., HOLLOWAY, G. A. JR. (1978). An instrument to measure culaneous blood flow using the Doppler shift of laser light. *IEEE Trans Biomed. Eng.* **25,** 28–33.