PERIPHERAL RESISTANCE MEASUREMENT IN THE ASSESSMENT OF RUNOFF IN FEMORODISTAL BYPASS GRAFTING

Simon Dudley Parvin

A thesis submitted to the University of Leicester

for the degree of Doctor of Medicine

Department of Surgery, University of Leicester

April 1987

UMI Number: U008696

All rights reserved

INFORMATION TO ALL USERS
The quality of this reproduction is dependent upon the quality of the copy submitted.

In the unlikely event that the author did not send a complete manuscript
and there are missing pages, these will be noted. Also, if material had to be removed,
a note will indicate the deletion.

UMI U008696
Published by ProQuest LLC 2015. Copyright in the Dissertation held by the Author.
Microform Edition © ProQuest LLC.
All rights reserved. This work is protected against
unauthorized copying under Title 17, United States Code.

ProQuest LLC
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106-1346

PERIPHERAL RESISTANCE MEASUREMENT IN THE ASSESSMENT OF RUNOFF IN FEMORODISTAL BYPASS GRAFTING

Simon Dudley Parvin

Vascular reconstruction beyond the inguinal ligament is a well established technique but the results are poor compared with more proximal reconstructions. The state of the vessels distal to the site of graft insertion is a major factor in determining the outcome. Arteriography, the main means of assessment of this runoff, is subjective and unreliable. Using the analogy to Ohm's law a quantitative assessment of runoff has been made by calculation of peripheral resistance from measurement of pressure created by a known flow of blood infused into the vessel under study.

Resistance was measured in two groups of dogs, and in three groups of patients undergoing amputation, femorotibial or femoropopliteal reconstruction. Both constant pressure and constant flow measurements were applied with blood, saline and Dextran.

The dog work showed that resistance fell with increasing flow, so that to make comparisons between individuals necessitated measurement at a fixed flow. Results were very reproducible despite the varying sizes of the animals. The concentric cannula technique for pressure mesurement was shown to be more accurate than direct stab or sidearm measurement. The constant pressure technique, whilst correlating well with the constant flow technique, was cumbersome and impractical. Saline and Dextran were both suitable for resistance measurement but neither carried any specific advantages over blood.

Resistance in the amputation, femorotibial and femoropopliteal groups correlated with; severity of disease defined by type of operation; level of graft insertion in the leg; and runoff defined by a comprehensive assessment of the arteriogram. Resistance was significantly higher in failed grafts than patent grafts upto six months after operation, and a cutoff level of resistance of 1200mPRU was a highly significant predictor of outcome. Similar results were achieved after drug induced vasodilatation.

Resistance measurement has proved a useful predictor of outcome in femorodistal reconstruction.

PERIPHERAL RESISTANCE MEASUREMENT

Contents

LIST OF FIGURES

PERIPHERAL RESISTANCE MEASUREMENT

Chapter 8

PERIPHERAL RESISTANCE MEASUREMENT

STATISTICS

Except where stated in the text, all comparisons in this thesis have been tested using the single tailed Mann Whitney U test. Calculations have been made on a BBC microcomputer using a 'University Software' statistics package called Unistat. P values have been obtained from 'Nonparametric Statistics for the behavioural sciences' by Sidney Siegal (McGraw-Hill Kagakusha Ltd).

CHAPTER 1

INTRODUCTION

The introduction of intraluminal valve disrupters which led to the introduction of in situ femorodistal grafting has meant that vascular surgeons have become able to bypass more distal blocks in the femoral and popliteal arteries than was previously realistically possible using the reversed vein.

With this new freedom came the problem of assessing the runoff distal to the site of graft insertion. The available runoff plays an important role in determining outcome in femorodistal reconstruction. The conventional method for its assessment has been arteriography but there is evidence that it is inadequate when assessing more distal disease. Assuming that the runoff is an important factor in influencing the patency of the graft another method of assessment of runoff would seem to be required.

Quantitative measurement of runoff is an attractive proposition for three reasons. Firstly it might permit more precise definition of runoff. Secondly it might allow comparisons to be made between patients making for a more logical treatment regimen for any one individual. Thirdly it might allow more meaningful

comparisons to be made between the results of different centres.

The aims of this thesis have been to investigate the usefulness of an objective measurement of distal runoff in patients prior to reconstructive surgery. Resistance measurement has the potential to quantify runoff in the distal vascular tree and can be measured using the analogy to Ohm's law.

There are inherent difficulties in the accurate determination of flow, but pressure can be accurately measured quite easily. In this thesis resistance has been calculated by infusion of blood at a known flow rate with accurate measurement of the resulting pressure generated in the distal vasculature.

The first three chapters of the thesis review the general management of peripheral vascular disease, the role of flow and pressure measurement in the prognosis of vascular reconstruction, and previous work on peripheral resistance measurement. In Chapter 5 a pilot study of resistance measurement in the dog has been undertaken in order to assess its feasibility and reproducibility. In Chapter 6 a small group of patients having amputation have been studied using the same criteria. In Chapter 7 the method of pressure measurement is assessed, the type of infusion fluid is studied, and comparisons are made between constant

pressure and constant flow measurement of resistance. In Chapter 8 which is divided into six sections patients undergoing either femorotibial or femoropopliteal reconstruction have been studied in some detail employing modifications of the method derived from Chapter 7. A summary of the results and important conclusions are found in Chapter 9.

ACKNOWLEDGEMENTS

Although the author was responsible for the vast majority of the work in this thesis it would not have been possible without considerable technical assistance. The Department of Medical Physics at the Leicester Royal Infirmary and in particular Steven Bentley and Mike Asher were responsible for the accurate recording of all the data. Each spent many hours making measurements both in the operating theatre and during the animal experiments. Dr David Evans gave much appreciated advice and some assistance with the statistics. I am indebted to Professor Bell for allowing me to study his patients and for all his encouragement throughout my time in the Department of Surgery in Leicester.

CHAPTER 2

OCCLUSIVE ARTERIAL DISEASE

INCIDENCE

Peripheral vascular disease is a common problem with a prevalence in the United States estimated to be 2-3% in men aged 45-60, and 1% in women aged 50-65 (Kannel, Wolf, Verter and McNamara 1970). There were 156,000 deaths due to ischaemic heart disease, 67,000 deaths due to cerebrovascular disease, and 15,000 deaths due to peripheral arterial disease in 1983 (OPCS 1983). Women lag behind men by approximately 10 years. In 1983 approximately 17,000 reconstructive operations were performed on arteries with a male to female ratio of 2:1. There were 14,900 amputations. Of these 2170 were primary below knee amputations and 3210 were above knee. (DHSS 1983).

ATHEROMA

Peripheral vascular disease is the clinical manifestation of atheroma, a condition in which the arterial wall becomes thickened and calcified and plaques of fat, platelets and thrombus are deposited in the intimal layer resulting in narrowing of the vessel. A number of theories exist to explain the

mechanism of atheroma formation (French 1971, Kao, Wissler and Dzoga 1968, Benditt 1977 and Baumgartner 1974). All arteries are affected by this process to a greater or lesser extent, but medium sized arteries of the coronary and cerebral circulation are particularly at risk resulting in the high mortality mentioned above.

RISK FACTORS

Known exacerbating risk factors include smoking, diet, ageing, male sex, hypertension, raised blood cholesterol, diabetes mellitus, and a strong family history (Hughson, Mann and Garrod 1978a). There is strong evidence that smoking is implicated in the aetiology of atheroma. The risk of developing atheroma is fifteen times higher in males and seven times higher in females who smoke (Hughson, Mann, Tibbs and Woods 1978b) than in those who do not. It is estimated that 25% of the deaths each year due to cardiovascular disease are associated with smoking. Post mortem studies reveal a significantly higher proportion of patients with severe atheroma among smokers (46%) than non-smokers (15%) (Auerbach, Hammond and Garfinkel 1965). The Framingham study (Kannel and Shurtleff 1973) reported cigarette smoking to be an independent factor in the aetiology of intermittent claudication.

The association between diabetes mellitus and peripheral vascular disease has been known for some time (Brandman and Redisch 1953). The diabetic patient has more distal vessel involvement (Strandness, Priest and Gibbonds 1964) and usually more extensive vascular calcification. It has been suggested that there are extensive arteriovenous fistulae in the microcirculation with increased velocity of blood flow and shunting (Scarpello, Martin and Ward 1980, Edmonds, Wilton, Roberts et al 1980 and Ward 1982). The normal ischaemic changes of an arteriopath are accentuated by the peripheral neuropathy of diabetics (Watkins 1982).

SYMPTOMATOLOGY

The severity of symptoms from the atheroma bears little relation to the extent of the disease. Quite severe disease may result in minimal symptoms particularly when the disease has progressed slowly over many years. This is because collateral vessels enlarge and bypass stenotic segments, so that when the main vessel eventually thromboses there is a good collateral supply established which protects the distal circulation. Collateral vessel growth is thought largely to be due to the pressure gradient around the block (John and Warren 1961) though release of vasoconstrictor

tone in the collateral vessels (Edwards, Cohen and Marshall 1959) and accumulation of metabolites may play a part. Conversely an acute arterial thrombosis in an otherwise almost normal limb, as may occur with embolism, can result in severe ischaemia owing to the lack of collaterals.

In its mildest form peripheral vascular disease presents as a superficial femoral occlusion with intermittent claudication causing pain in the calf during exercise. The pain is characteristically tight and cramplike and is always relieved by rest. Aorto-iliac disease with internal iliac occlusion may result in the Leriche syndrome with impotence and buttock pain on walking. The natural history of intermittent claudication depends partly on the risk factors. If the patient stops smoking and takes regular exercise the condition often runs a benign course over many years either remaining static or improving (Quick and Cotton 1982; Juergens, Barker and Hines 1960; and Mathieson, Larsen, and Wulff 1970). If this simple advice is ignored then the disease and symptoms may progress so that the claudication distance shortens and the patient eventually develops pain at rest. Coupled with this rest pain is the risk of developing gangrene in the digits. At this stage the limb is threatened and if feasible, reconstructive surgery is indicated

(Bell, Charlesworth, DePalma et al 1982). If not then major amputation may be needed.

This process of atherosclerosis is fortunately patchy, characteristically affecting one or more of three main sites; the aorto-iliac segment, the femoropopliteal segment, and the distal tibial vessel segment. It is unusual for the disease to be confined to one site, and not uncommon for all sites to be affected together.

INVESTIGATIONS

Investigation of patients with peripheral arterial disease begins with a simple assessment of the risk factors. Diabetes and the hyperlipidaemias are diagnosed biochemically. Hypertension and ischaemic heart disease are diagnosed by accurate blood pressure measurement (Kirkendall, Burton, Epstein et al 1967), ECG and chest X-ray. Non-invasive investigations specific to the arterial disease may also be performed. Doppler examination may be used to look for patent smaller arteries (Roedersheimer, Feins and Green 1981) and at the quality of larger arteries. The ankle/brachial pressure index indicates the severity of the disease (Yao, Hobbs and Irvine 1969 and Heintz, Bone, Slaymaker et al 1978) and can be used

together with post exercise measurements of the same ratio (Nicolaides 1978 and Chamberlain, Housley and Macpherson 1975) to monitor its progress. Non-invasive estimates of blood flow into the limb may be made with the plethysmograph (Whitney 1953 and Linhart, Dejdar, Hlavova et al 1974), isotope clearance techniques (Angelides and Nicolaides 1980 and Hurlow ,Chandler, Hardman et al 1978), xeroarteriography (Kramann 1979) and ultrasound measurement of Doppler shift (Gill 1985). The results of plethysmography have proved difficult to reproduce (Nielsen, Bell and Lassen 1973). Doppler waveform analysis from the femoral artery has been used to characterise stenosis in the aortoiliac segment by performing principal component analysis, transfer function analysis and by calculating the pulsatility index (Evans, Macpherson, Bentley et al 1981; Demorais and Johnston 1981; Archie and Feldtman 1982; Macpherson, Evans and Bell 1984; and Campbell, Cole , Skidmore et al 1984).

MANAGEMENT

Medical management of patients with claudication predominates over surgical management. A large number of drugs have been advocated. Among these are antilipaemic drugs, antiplatelet drugs, prostaglandins,

anticoagulants, vasodilators, rheological agents, and metabolic enhancers. Boobis and Bell (1982) in their review of the subject suggest that none of these drugs alone is of much use but that alteration of the platelet/vessel wall interaction holds out the best hope of progress.

Although not all cases can be treated by reconstructive surgery, the degree of success when this is performed is related to the site reconstructed. Proximal reconstruction has a very good graft survival rate with typical five and ten year cumulative patency rates of 85% and 66% respectively (Malone, Moore and Goldstone 1975). The results of femoropopliteal grafting are summarised in Figure 1 and those for femorotibial grafting in Figure 2. Unfortunately patients who are at most risk of gangrene and rest pain tend to have severe distal disease requiring distal reconstruction for which the results are least good.

FEMOROPOPLITEAL GRAFTS - SAPHENOUS VEIN

Author	Date	Number	Patency % (5 year)
Mixed claudication and salvage			
Myhre	1977	154	60
DeWeese	1977	113	59
Szilagyi	1979	464	56
Claudication only			
Baddeley	1970	185	62
Koontz	1972	74	64
Cranley	1981	416	72
Salvage only			
Naji	1978	100	66
Reichle	1979	310	60
Veith	1981	318	50

Figure 1

FEMOROTIBIAL GRAFTS

Author	Date	No	Graft	Patency %	
				1yr	5yr
Reichle	1979	164	LSV	54	47
Mason	1982	17	LSV	75	
Veith	1981	204	LSV/PTFE	64	47
Dardik	1975	32	LSV	57	
Dardik*	1979	61	LSV	55	
Edwards	1976	97	LSV	74	
Nicholas	1973	44	LSV	70	61
Imparato	1974	81	LSV	56	52
Bernhard	1972	41	LSV	63	

* All peroneal reconstructions

Figure 2

SURGICAL MANAGEMENT

Despite the availability of large numbers of investigations the decision to attempt reconstructive surgery remains a clinical one, based on clinical assessment of the severity of the disease at the time, and the likely outcome of withholding surgery. Having made the decision to operate, the patient is normally subjected to invasive investigation. Arteriography is an essential adjunct to routine reconstruction though it may be omitted in some acute situations. It serves three purposes. Firstly, it defines the state of the proximal vascular tree (the inflow). Secondly, it shows the femoropopliteal segment although this can usually be assessed clinically and non-invasively. And finally, in expert hands, it may show the distal runoff beyond the knee into the foot. In the assessment of any one artery it provides information on whether or not the vessel is patent at all, and if so on its calibre, runoff, number of stenoses and their position, and on two dimensional arteriography the severity of the stenosis.

In the proximal aorto-iliac segment the operation required is usually obvious and arteriography merely confirms the clinical assessment. Because the results of reconstructive surgery in this region are so good

minor irregularities in the aorta or distally in the femoropopliteal segment can be ignored since they are unlikely to alter the outcome significantly.

In the femoropopliteal segment, however, where a failed operation may lead to amputation if the operation is being performed for critical ischaemia, and where the ensuing amputation may be at a higher level than if the patient had been subjected to primary amputation (Sethia, Berry, and Morrison 1986), the quality of the runoff is more important. The outcome of grafting to this level has been shown to correlate with the number of vessels communicating directly with the popliteal artery and then down into the foot (Deweese and Rob 1977; Koontz and Stansel 1972; Cutler, Thompson, Kleinsasser et al 1976; and Naji, Chu, Mccombs et al 1978). Stenoses affecting the runoff at this level are more important in determining outcome but it is usually possible to make a reasonable subjective assessment of the runoff from the arteriogram.

Assessment of the distal arterial tree is much less certain. The quality of the films is less good because there is considerable dilution of contrast before it reaches the region of interest. This can be improved by using reactive hyperaemia as described by Kahn, Boyer, Moran et al (1968) and Feins, Roedersheimer, Baumstark et al (1981). The addition of

ultrasonic detection of the arrival of contrast in the periphery by James and Galloway (1971) and Soulen, Tyson, Reichle et al (1973) has further improved the film quality. Shearman, Gwynn, Curran et al 1986 have suggested that it is possible to assess the popliteal segment noninvasively and Roedersheimer, Feins and Green (1981) have shown that the presence of a patent pedal arch can be accurately assessed by ultrasound alone.

The outcome of vascular replacement to the distal tibial or peroneal arteries at ankle level is significantly worse than that achieved with the femoropopliteal replacements (Figure 2). The potential runoff at this distal level is strictly limited. To be forced to graft to ankle level implies the absence of patent vessels higher up in the calf or at popliteal level. The runoff is therefore limited to the foot, supplying mainly skin and bone. The resultant flow as shown by Harris and Campbell (1983), is rarely in excess of 75ml/min and this is unlikely to be sufficient to maintain graft patency.

OUTCOME

The outcome of reconstructive vascular surgery depends upon several factors. Local factors include the quality of the runoff, the state of the inflow vessels (Charlesworth, Harris, Cave et al 1975), the size

(Koontz and Stansel 1972) and type of graft used for the bypass, and the site and angle of insertion of the distal end of the graft (Klimach, Underwood and Charlesworth 1984). Whilst synthetic materials are quite satisfactory for proximal reconstructions it is generally held that autogenous vein, either reversed or in situ, is best for distal reconstruction (Bergan, Yao, Flinn et al 1982 and Hall 1962). When the vein is not available, umbilical vein and polytetrafluoroethylene grafts have been used but with lower success rates (Bergan, Yao, Flinn et al 1982; Klimach, Underwood and Charlesworth 1984, and Charlesworth, Brewster, Darling et al 1985). Indirect factors include the seniority of the surgeon performing the operation, the general condition of the patient, the presence of diabetes, or heart disease, perioperative hypotension, and blood loss. Late indirect factors include progression of disease, continued smoking (Myers, King, Scott et al 1978), diabetes, the development of pseudointimal hyperplasia (Beard and Fairgrieve 1986), treatment with anti-platelet drugs (Goldman, Hall, Dykes et al 1983) or Warfarin (Kretschmer, Wenzl, Wagner et al 1986), and the use of a graft which crosses the knee joint.

CONCLUSION

Femorodistal reconstructive surgery has now been performed for over twenty years. The results of these operations are inferior to those achieved in the more proximal reconstructions. It is generally accepted that vascular reconstruction is always preferable to amputation (Bell 1985), and therefore vascular surgeons are obliged to continue searching for methods which separate those patients in whom a graft will succeed from those in whom it will fail. The outcome of vascular reconstructive surgery is obviously multifactorial and one of the more important factors must be the state of the distal circulation at the time of surgery. The remainder of this thesis examines methods of assessing the distal circulation prior to reconstruction with the aim of separating a group of patients in whom reconstruction is hopeless from one in whom it might be expected to succeed.

CHAPTER 3

PRESSURE FLOW AND IMPEDANCE

Kolin (1936) and Wetterer (1937) independently developed flowmeters based on Faraday's Law of electromagnetic induction. The square wave electromagnetic flowmeter principle was introduced in 1955 by Denison and Hall. In the early 1960's the clinical use of electromagnetic flowmeters increased so that it became possible to measure flow accurately after reconstructive surgery. Early measurements were made in patients undergoing varicose vein surgery where it was possible to mobilise the femoral artery at the same time (Schenk, Menno, Anderson et al 1960). Flow was shown to increase with vasodilators, lumbar sympathectomy and X-ray contrast media injected intra-arterially. The accuracy of early machines was fair (Golding and Cannon 1966 and Dedichen 1974) but it was pointed out that poor fit of the probe to the vessel and atheroma could increase the error considerably. The importance of measurement of augmented flow with papaverine was stressed with the mean increase in flow being approximately 100%. Golding and Cannon also suggested that pressure measurement without concomitant flow measurement was of limited value in the assessment

of success of reconstructive surgery.

The normal flow in the common femoral artery has been shown to be 239 ml/min. In the superficial femoral artery flow was 134 ml/min and in the profunda artery 104 ml/min (Vanttinen 1975). Similar flows have been observed by Lewis, Psaila, Davies et al (1986) using a Duplex scanner. The papaverine response in the normal femoral segment was an increase in flow of 250%. The prognostic potential of flow measurement was described by Little, Shiel, Loenthal et al (1968). After femoropopliteal grafting flow of less than 60 ml/min was associated with a 80% chance of early graft failure whilst flow greater than 60 ml/min was associated with 80% patency in the first three months. Cappelen and Hall (1967) had a 10% failure rate with flow greater than 100 ml/min and a 50% failure rate with flow less than 100 ml/min. Terry, Allen and Taylor (1972), Sonnenfeld, and Cronestrand (1980), and Dedichen (1976) achieved similar results. Roberts and Cotton (1977) found no significant difference in flow after profundaplasty between those with successful outcome (107ml/min) and failures (78 ml/min). There were significant differences in flow velocity and it was suggested that this might be a more useful measurement. Scheinin and Inberg (1968) suggested that if there was not a significant increase in blood flow after the

administration of papaverine after vascular reconstruction then there was probably a technical error in the anastomosis. Immediate lumbar sympathectomy was shown to be of benefit if the reconstruction was otherwise deemed inadequate. Dedichen (1973) looked simultaneously at graft flow and pressure gradient across either an implanted graft or the endarterectomised segment of a femoral artery. He encountered similar results to Terry, Allen and Taylor and Cappelen and Hall and found only very small pressure gradients along the femoral segment or graft. He suggested that the resistance of the graft was minimal compared with the resistance distal to the reconstruction and that distal disease was the primary cause of early graft failure. In a further paper Dedichen (1975) noted that after reconstruction the flow increase due to papaverine was greater than that following five minutes of tourniquet occlusion of the leg confirming the usefulness of papaverine to induce maximal flow.

Pressure measurement alone is of limited use in the prediction of outcome of femorodistal reconstruction. Ankle/brachial pressure index measurement provides a rough idea of the severity of disease but is of no use as a predictor of outcome after surgery. Agerskov, Faris, Tonnesen et al (1983)

measured popliteal artery pressure by direct cannulation and compared it with indirect measurement of ankle pressure. The popliteal/ankle pressure difference did not correlate with outcome but did correlate with eventual ankle pressure six months after grafting. Crawford, Blaisdell, Morris et al (1963) measured pressure either side of a carotid bifurcation stenosis and noted that when the area reduction was in excess of 50% there was a significant reduction in distal pressure which could be reversed by surgery. In a similar study on the aortofemoral segment Weismann and Upson (1963) showed that decrease in femoral pulse assessed by palpation alone was inaccurate, that femoral pressure was decreased by iliac stenotic disease and that vascular replacement abolished the pressure gradient. Garrett, Slaymaker, Heintz et al (1977) showed that if the increase in ankle/brachial pressure index after aortoiliac reconstruction was <0.1 the clinical outcome was unsatisfactory. Similar results have been observed in patients undergoing femoropopliteal reconstruction (Lewis 1974 and Wood, Bishara and Darke 1985). Wood also assessed the technical adequacy of surgery with the same technique. Mannick, Jackson and Coffman (1966) suggested that if popliteal artery pressure could be raised above 75 mmHg by bypass grafting claudication would be abolished even in the

presence of severe distal disease. Dedichen (1976) studied the pressure gradient before and after reconstruction of both the aortoiliac and femoropopliteal segments and demonstrated almost complete abolition of the gradient after surgery. When a successful bypass was performed the ensuing gradient was slightly less than that measured when there was primary graft failure but the difference was not great enough to be used in a predictive way.

In their paper Evans, Quin and Bell (1980) emphasise the need to consider the results of pressure measurements in the light of the simultaneous changes which might be occurring in flow. It is also suggested that to be meaningful pressure measurement should be made at constant flow and preferably by direct cannulation of the artery being studied.

Impedance is an expression of the total opposition to blood flow in an artery and includes the effects of elasticity, inertia, reflection, and viscosity in the vessels beyond the point of measurement. Impedance measurement in normal dogs (O'Rourke and Taylor 1966) and humans (McDonald 1974) has been well described. Results were consistent and reproducible. Farrar, Malindzak and Johnson (1978) described the changes in impedance that occurred when a stenosis was introduced into the circulation both in an

experimental animal and in the human with atherosclerosis and noted that it provided a measure of the severity of disease. Cave, Walker and Naylor (1976) measured impedance at the time of, and three months after femoropopliteal grafting and showed significant differences in the successful group. Law, Graham, Cotton et al (1983) were able to substantiate these results in the aortoiliac group but not in the femoropopliteal group although the same trend existed. Impedance measurement alone has not been used to determine the outcome prospectively in patients undergoing femoropopliteal reconstruction.

CONCLUSION

Impedance and pressure measurement have not proved useful alone in determining the outcome after femorodistal reconstruction. The evidence for impedance is controversial and more work is required. Pressure measurement might be useful for deciding whether the reconstruction performed is technically adequate, and for the longterm follow-up of patients following vascular reconstruction. Flow measurement alone does seem to correlate with the outcome of reconstructive surgery and can also be used to assess the technical adequacy of the procedure. Of the three methods of assessment flow seems the most promising but none

appears to be the complete answer.

CHAPTER 4

PERIPHERAL RESISTANCE

The concept of peripheral resistance owes much to the work of Poiseuille (1799-1869), a physicist as well as a physician who originally intended his studies to be of the flow properties of blood. He was however unable to anticoagulate it and so turned to study the flow of pure liquids in rigid glass tubes. The Poiseuille equation states that pressure drop is directly proportional to the length of the pipe, to the rate of flow, and to the viscosity and inversely proportional to the fourth power of the radius.

$$Q = \frac{(P1-P2)R^4}{8\mu L}$$

Q = Flow
P = Pressure
R = Radius
L = Length
μ = Viscosity

The Poiseuille equation

The equation relates flow and pressure of a Newtonian fluid in a cylindrical tube. A Newtonian fluid was defined by rotating a rod in a fluid bath. He noted that 'the resistance which arises from the defect of slipperiness of the parts of the liquid other things being equal is proportional to the velocity with which the parts of the liquid are separated from oneanother'. The hypothesis emphasized that there were lamellae of

fluid slipping on oneanother at different velocities. There is thus a velocity gradient in a direction perpendicular to the surface, the gradient being known as the rate of shear.

$$T = \frac{dv}{dr}$$

T = Stress
$\frac{dv}{dr}$ = Velocity gradient
r = Distance from the axis

Rate of shear

If the flow is steadily increased then the resistance to flow eventually increases quite sharply and the Poiseuille equation then no longer applies. At this time flow ceases to be streamlined and laminar and becomes turbulent. This critical point is dependant on the diameter of the tube, the mean velocity of flow, the density, and the viscosity of the liquid. It is expressed as the dimensionless quantity known as the Reynolds number.

$$Re = \frac{VDp}{\mu}$$

V = Average velocity
D = Diameter
p = density

Reynolds number

When applied to the circulation certain assumptions have to be made regarding the Poiseuille equation.

1. The fluid is homogeneous. If the Diameter is large then the blood despite containing particles (red cells) behaves like a Newtonian fluid.

2. The viscosity is the same at all shear rates. When the vessel diameter is small there is an apparent change in viscosity owing to the presence of the red cells.

3. The liquid velocity immediately adjacent to the wall is zero. This is the case with blood and all other liquids, although it was felt that if the vessel was not wettable there might be some slip.

4. The flow is laminar. In large vessels with no disease this is probably true, but when the vessel is small or diseased Reynolds number is certainly exceeded and turbulence ensues.

5. The flow is steady. If the velocity of flow is altered the pressure gradient imparts some kinetic energy to the liquid and Poiseuille's equation does not apply. It does not therefore apply to pulsatile flow.

6. The tube is long compared to the region being studied.

7. The tube is rigid and diameter does not vary with internal pressure. Large arteries are elastic and flow is therefore not solely dependant on the pressure gradient. Smaller vessels and capillaries behave like rigid tubes and Poiseuille's equation applies.

It can be seen from the above conditions that the human circulation approximates only very roughly to the Poiseuille equation, and that further application of the equation must necessarily introduce errors.

The concept of an analogy to Ohm's Law for the measurement of peripheral resistance has been used in this thesis.

V = IR	V = Potential difference I = Current R = Resistance
P1-P2 = QR	P1 = Arterial pressure P2 = Venous pressure Q = flow R = Resistance

Resistance is expressed in PRU (peripheral resistance units), where

1PRU = 1mmHg pressure drop / 1 ml/min flow
1PRU = 1000mPRU

Measurement of impedance implies a measurement of resistance under pulsatile flow conditions. Resistance measurement is performed at constant flow and reconsideration of conditions for the application of Poiseuille's equation shows that more of the conditions are met under these circumstances.

Whittaker and Winton (1933) summarised the previous work on blood viscosity and used an isolated dog hindlimb preparation in their own studies. It was noted that if the perfusing solution was changed from blood to Ringers solution then flow increased by approximately three times at the same pressure. For both blood and Ringers solution it was found that there was a linear relationship between pressure and flow and that at all but the lowest flow rates the Poiseuille equation

applied. The haematocrit of the infused blood was also varied and it was noted that for a given pressure the flow achieved was inversely proportional to the haematocrit. The relationship between apparent viscosity and haematocrit was linear upto a haematocrit of 0.50, but viscosity increased steeply above this level. Although not deliberately the case, these experiments were performed at maximal vasodilatation by virtue of having an isolated hindlimb preparation.

In contrast, Pappenheimer and Maes (1942) studied a perfused dog hindlimb preparation at varying degrees of vasoconstriction. It was shown that blood flow was not proportional to the perfusing pressure. Vasoconstriction at low perfusion pressure resulted in a non linear relationship between flow and pressure. Only when the pressure reached 100mmHg was there an approximately linear relationship. There was no change in resistance with pressure when perfusing with Ringers solution, and it was concluded that the change in resistance brought about by vasoconstriction was the result of a change in the apparent viscosity of the blood as well as of a change in the dimensions of the blood vessels. It was also shown that there was a wide variation in resistance between dogs measured at any one pressure with similar degrees of vasoconstriction suggesting that there was a variable number of perfused

vascular elements present. These two papers suggest that measurement of resistance at maximal flow might exclude errors induced by a change in apparent viscosity when vasoconstriction is present.

Green, Lewis, Nickerson et al (1945) measured resistance in three vascular beds :- the skin of the thigh, quadriceps, and gastrocnemius and soleus of the dog. The definition of peripheral resistance units was coined and unlike their predecessors found a non-linear relationship between pressure and flow. The curve was sigmoid in shape. However they agreed that a high flow there was a linear relationship between pressure and flow. The probable explanation for the non-linear part of the curve lies in the fact that the critical opening pressure is not reached until quite high pressures are attained. Thus at low flow rates the resistance is higher than expected.

Pappenheimer and Soto-Rivera (1948) by performing dog and cat isolated hindlimb preparation experiments were able to show that resistance increased greatly as flow was reduced by reducing the perfusion pressure.

Hanson and Johnson (1962) studied arterial and venous resistance in an isolated auto-perfused canine hindlimb and described three types of resistance/pressure curves. Resistance was shown to either increase steadily, decrease steadily, or

initially increase and subsequently decrease as pressure was reduced. These variations were not adequately explained by the authors and were at odds with the findings of Pappenheimer and Soto-Rivera (1948).

Vetto and Dunphy (1964) were the first to put peripheral resistance measurement to use in humans. Disappointed by the high failure rate of femoropopliteal reconstructions they measured peripheral resistance as a prognostic indicator in the popliteal artery prior to reconstructive surgery. Cold bank blood was pumped into the popliteal artery at a known flow rate and pressure generated in the artery was measured with a separate cannula. Resistance was calculated in dyne-sec cm^-5. Six patients were studied and there was a reasonable correlation between early outcome and resistance. It is not clear however if all the measurements were made at the same flow rate and if so what that flow rate was.

Conrad and Green (1964) studied digital vascular resistance in a group of fourteen patients with vasospastic diseases and eleven asymptomatic medical students as controls. Digital blood flow was estimated with an airfilled plethysmograph and pressure was estimated using the plethysmograph cuff. It was shown that in normals the resistance was moderately high in the resting state but reduced to about one third after administration of alcohol. Resistance in the patients

was markedly elevated at rest and fell with alcohol though not to normal levels. The most striking finding was the extreme 'normal ' variation in resistance in the control subjects - a factor of 27 times at rest and six times after alcohol.

Weale, Taylor and Rothwell-Jackson (1964a) measured resistance in two groups of patients. Controls had their femoral arteries exposed for cytotoxic drug administration for management of their malignant melanoma or were having aneurysm repair. Study patients had popliteal artery resistance measured prior to femoropopliteal arterial reconstructive surgery. The technique (Weale 1964b) was a constant pressure one with readings being taken in the physiological range. Results showed that resistance at groin level was significantly lower than that measured in the popliteal artery (P=0.012) Mann-Whitney U test. It was noted that resistance was higher when the perfusing pressure was low and it was suggested that this was a manifestation of the collateral circulation.

Folse (1965a and 1965b) measured femoral resistance in 26 patients with femoropopliteal occlusion using a dye dilution technique to measure flow. Measurements were made both at rest and after exercise. Mean results for all the patients were presented and showed the resistance to be low at rest but to fall with

exercise.

Delin and Ekestrom (1965) measured resistance in patients before and after surgery for occlusive vascular disease. In each case resistance fell after surgery but the resistance was not measured at the same flow rate and under these circumstances comparison of resistance values is not possible.

Mundth, Darling, Moran et al (1969) measured resistance in patients undergoing femoropopliteal vein grafting before and after reconstruction. Arteriography did not correlate well with resistance measurement, but neither was there any correlation between resistance and patency. As with Delin and Ekestrom (1965) resistance was measured at different flow rates making interpretation of results difficult.

Bliss (1971) in an excellent paper measured resistance in 23 patients undergoing femoropopliteal grafting. By his technique he was able to maintain a continuous infusion of the patients own blood into the popliteal artery prior to reconstruction. Using a concentric cannula of his own design he was able to measure pressure in the popliteal artery at the same time as infusing. Resistance was measured at a number of flow rates and before and after papaverine. He showed that resistance varied tremendously from patient to patient under the same conditions. Resistance fell and

sometimes increased with increasing perfusion pressure and flow, and the shape of the pressure/flow curve varied considerably. Papaverine increased the variation measured - a finding at odds with those of Conrad and Green (1964). In general, resistance fell with increasing flow and pressure and reached a steady level at flows in excess of 200ml/min. He suggested that at these flow levels it should be possible to make comparisons of resistance between two subjects. He concluded by saying that the resistance was made up from vasomotor tone and 'fixed arterial resistance' caused by stenoses and blocks, and that if an estimate of fixed arterial resistance was required then steps must be taken to minimise the vasomotor tone by giving a peripheral vasodilator.

In a further paper Bliss (1973) showed that resistance correlated well with runoff defined arteriographically but could not show any correlation between resistance and graft patency. These measurements were however made postoperatively and at a number of different flow rates from 128-230ml/min, making comparison between patients impossible.

Barner, Kaminski, Codd et al (1974) measured resistance in 74 patients after completion of femoropopliteal reconstruction. No difference in resistance between subsequently patent and occluded

grafts either at basal or peak augmented flow rates was noted. Neither could they show any difference in relation to the number of vessels patent to ankle level.

Sonnenfeld, Cronestrand, and Nowak (1979) and Sonnenfeld, Cronestrand, Von Euler et al (1981) measured resistance after femoropopliteal reconstruction in eleven patients. Blood transfusion immediately after reconstruction resulted in a reduction of peripheral resistance as did the administration of papaverine. It was concluded that the transfusion effect was secondary to hypovolaemia.

Serise, Le Heron, Janvier et al (1982) measured resistance in 22 patients undergoing femoropopliteal grafting. Saline was injected at 30ml/min in each case. A technical error was found in one of 17 patients with a resistance of < 3.0 PRU whose graft occluded early. When the resistance was > 4.0 PRU there were 4/5 early thromboses, and when the resistance was > 5.0 PRU every graft failed.

Menzoian, La Morte and Cantelmo (1985) performed resistance measurements in five dogs and 23 humans undergoing femoropopliteal reconstruction. A Harvard pump was used to perfuse the artery under study at known flow rates and pressure was recorded via a sidearm catheter. Resistance was measured at a number of predetermined flow rates. Blood was used for perfusion

in the dogs and saline was used in the human experiments. In both dogs and humans there was a significant change in resistance as flow increased from 50-200 ml/min. There was considerable variation in resistance from patient to patient. Preoperative arteriograms were awarded a score from 1-4 according to the severity of the disease and there was a very poor correlation between this score and the resistance.

SUMMARY

There is comparatively little work in the literature on the use of peripheral resistance measurement in the assessment of patients undergoing reconstructive vascular surgery. Early work showed that resistance depended on the viscosity of the perfusing solution (Whittaker 1933). It was shown that the relationship between pressure and flow was non-linear (Pappenheimer 1942; Green 1945) but that at high flow rates the relationship was approximately linear. There were considerable differences of opinion as to the shape of the pressure/flow curves (Hanson 1962; Pappenheimer 1948; Weale 1964a; Bliss 1971). The majority accept that the resistance falls with increasing flow and pressure (Green 1945; Pappenheimer 1948; Conrad 1964;Weale 1964). The need for maximal flow conditions for the measurement

of resistance remains contentious with Whittaker (1933); Conrad (1964); Folse (1965); and Sonnenfeld (1979 and 1981) in favour, but with Bliss (1971) and Barner (1974) unable to show any advantages. In the early studies on patients neither flow nor pressure were fixed (Vetto 1964; Delin 1965; Mundth 1969; Bliss 1973) and since there is a non-linear relationship between pressure and flow direct comparison between patients can only be made when the flow or pressure are fixed (Bliss 1973; Serise 1982; Menzoian 1985). Arteriography has been shown to correlate only poorly with resistance (Mundth 1969; Barner 1974; Menzoian 1985), but to correlate well by Bliss (1973). Probably the principal reason why resistance measurement has not become popular is that it has failed to correlate with graft patency (Bliss 1973; Mundth 1969; Barner 1974). In each of these papers resistance was measured at different flow rates and one may speculate that the poor correlation may in part be due to this fact.

CHAPTER 5

ANIMAL EXPERIMENT 1

Resistance measurement in an animal model

It has been shown in the preceding chapters that neither pressure nor flow alone is able to predict graft outcome. Resistance measurement theoretically might be useful because of its ability to quantify runoff, radiological assessment of which has been shown to be unreliable.

Because of the difficulties eluded to in Chapter 4 a series of dog experiments have been performed the aims of which were to :-

(a) Discover a simple reliable method by which peripheral resistance might be measured.

(b) Investigate the reliability of the technique with particular reference to the reproducibilty of the results.

(c) Investigate the relationship between pressure and flow over a range of flows in an animal model.

METHOD

Dogs have been used in this study. Resistance has been measured in the superficial femoral artery of the

right hindlimb.

ANAESTHETIC

Each animal was given a general anaesthetic. Induction was achieved in each case with Thiopentone and was maintained with nitrous oxide and oxygen and an infusion of intravenous Hypnorm. Ventilation was performed by the administration of the gases by closed circuit ventilation connected to an appropriate endotracheal tube. At the end of each experiment the animal was destroyed by the administration of a large intravenous dose of barbiturate. During the procedure pulse, systemic blood pressure and central venous pressure were monitored by continuous recording on a chart recorder. In order to standardise the anaesthetic as far as possible, both during a single procedure and between different dogs, arterial blood gases were estimated at intervals during the experiment. Systemic pressure was measured by placing a 20 gauge plastic cannula into one of the lateral branches of the aorta. The tip of the cannula was positioned at the aortic orifice of the branch. The branch itself was ligated distal to the site of cannulation. The cannula was connected by a 100cm length of manometer tubing to a pressure transducer and thence via an appropriate

amplifier and filter system to a chart recorder. Central venous pressure was measured using a size 20 Longdwell catheter placed via a stab in the left jugular vein into the superior vena cava. The cannula was sewn to the skin to prevent its displacement. The cannula was connected in the same way as the systemic pressure cannula to the chart recorder. ECG was monitored continuously with leads connected to electrodes appropriately placed on the chest. Urine output was monitored by direct puncture and catheterisation of the bladder. Intravenous fluids were given through a cannula placed in a front leg vein. Enough fluid was given to maintain urine output and central venous pressure at physiological levels.

THE MODEL

Once anaesthetised the dog was placed on its back on the operating table and its legs were strapped out. Sandbags were placed alongside the body to prevent it from tipping over and to help prevent heat loss. The dog was laid on a warming blanket. A rectal temperature probe was connected to the electric blanket and the thermostat set to 38°C.

A single long incision was made extending from the xiphisternum above to the stifle distally. In the abdomen the incision was made in the midline down to a

point marked by a line perpendicular to the inguinal ligament passing through the emerging femoral artery. The incision was continued along this line and then along the course of the femoral artery.

The hindlimb was rendered ischaemic by the technique described by Johansen and Bernstein (1979). The terminal aorta , both internal iliac arteries, and the last ipsilateral lumbar artery were all ligated. All branches of the external iliac artery and superficial femoral artery from the origin on the aorta to a point in the distal thigh were ligated and divided. The superficial femoral artery itself was then ligated in the proximal part of the thigh completing the devascularisation of the limb.

Venous pressure was measured with a 20 gauge cannula. This was sited in a sidebranch of the femoral vein at groin level its tip just emerging into the femoral vein itself. The cannula was connected to a pressure transducer and then the chart recorder with a manometer line. Arterial pressure was measured by a similar cannula sited in a sidebranch of the superficial femoral artery distally in the thigh.

Blood was withdrawn into two 50ml plastic disposable syringes. 500 units of Heparin had previously been added to each syringe to prevent the blood from clotting. These syringes were then mounted onto a

Harvard pump (Fig. 3). Each syringe was connected to the other by a short manometer line and a 3-way tap. The two were then connected to the infusing cannula by another longer manometer line.

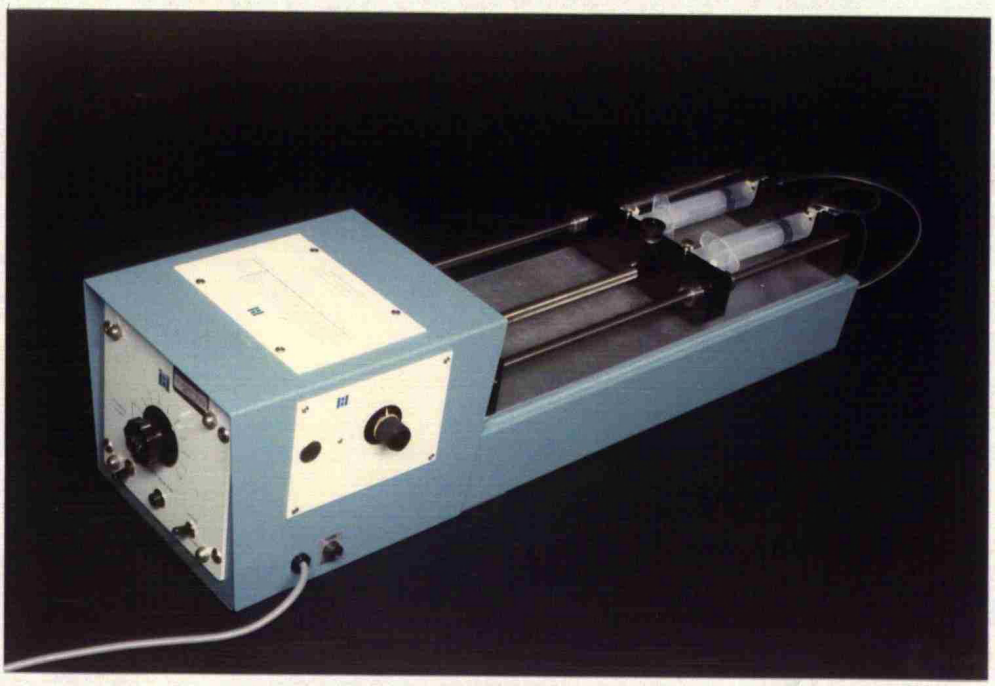
The infusing cannula was placed in the superficial femoral artery immediately distal to the site of its ligation and was snugged in place with a silastic sling. The completed model is shown in Fig. 4.

MEASUREMENT

Resistance was measured in the superficial femoral artery before it was ligated. Flow was measured with an electromagnetic flow probe placed around the superficial femoral artery.

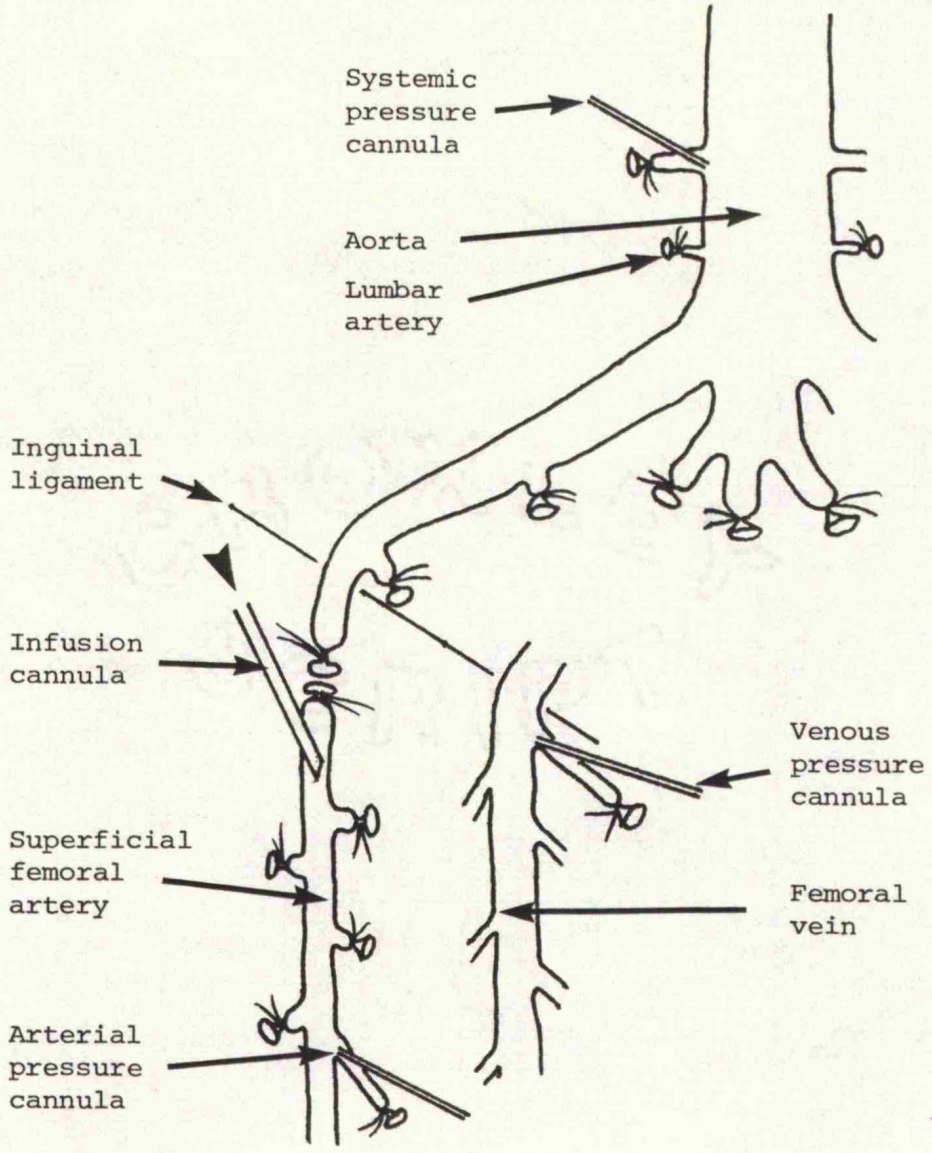
After ligation of the superficial femoral artery arterial and venous pressure were measured at a series of five different flow rates - 9.5, 19.1, 38.2, 76.4, and 190ml/min. Measurement was begun at the lowest flow rate and the flow was only increased when the arterial pressure had reached a plateau. When each of the flows had been tried once, the experiment was repeated with a further two syringes of blood after a delay of at least 20 minutes.

All pressures were measured with Elcomatic EM751 pressure transducers and recorded on a Gould 2800S



Two 50 ml syringes are mounted on the Harvard pump.

Figure 3



The completed dissection of the animal model

Figure 4

pressure ink direct writing recorder. Flow was measured with a Carolina 601D electromagnetic flowmeter using CF200 series flow probes. All parameters were recorded on a Racal 14DS multichannel instrumentation tape-recorder.

RESULTS

Before any measurements were made the accuracy of the Harvard pump was checked. There was no significant slowing in flow over a wide range of physiological resistances.

Details of the ten dogs used in this experiment are shown in Figure 5. Resistance was measured before ligation of the superficial femoral artery when the limb was still supplied with blood and was not yet ischaemic. Results for each dog are shown in Figure 6. The post-ischaemia resistance for each of the flow rates for all ten dogs is tabulated in Tables 1-5 in the Appendix (pages A2-6). Mean resistance for the two runs is shown in Figure 7. Prior to the introduction of ischaemia it will be noted that the range of flows into the hindlimb is 72-310ml/min, and that the resistance varies between 220-879 mPRU. The correlation between flow and resistance at this stage was good (r=-0.9033

p=0.0003).After the introduction of ischaemia the resistance fell in each case in comparison with the pre-ischaemia value. Direct comparison is not possible but reference to Figures 6 and 7 shows this to be the case at approximately equivalent flow rates. Figure 8 plots the mean resistance with standard error against flow for each of the dogs. It can be seen that resistance falls as flow increases.

DETAILS OF DOGS - EXPERIMENT 1

Number	Sex	Weight Kg	Fem art Diameter mm
1	M	28	5
2	M	32	4.5
3	M	28	4
4	F	29	4
5	F	33	4
6	M	30	4
7	F	30	5
8	F	27	4
9	M	33	4.5
10	F	23	4

Figure 5

RESISTANCE PRIOR TO ISCHAEMIA

Dog	Q	AP	V	Res
1	160	81	4.3	479
2	210	80	3.8	362
3	110	90	6.5	759
4	125	88	3.5	676
5	106	93	8.1	800
6	110	90	6.8	756
7	164	69	6.4	379
8	72	69	5.7	879
9	130	74	7.4	512
10	310	76	7.8	220

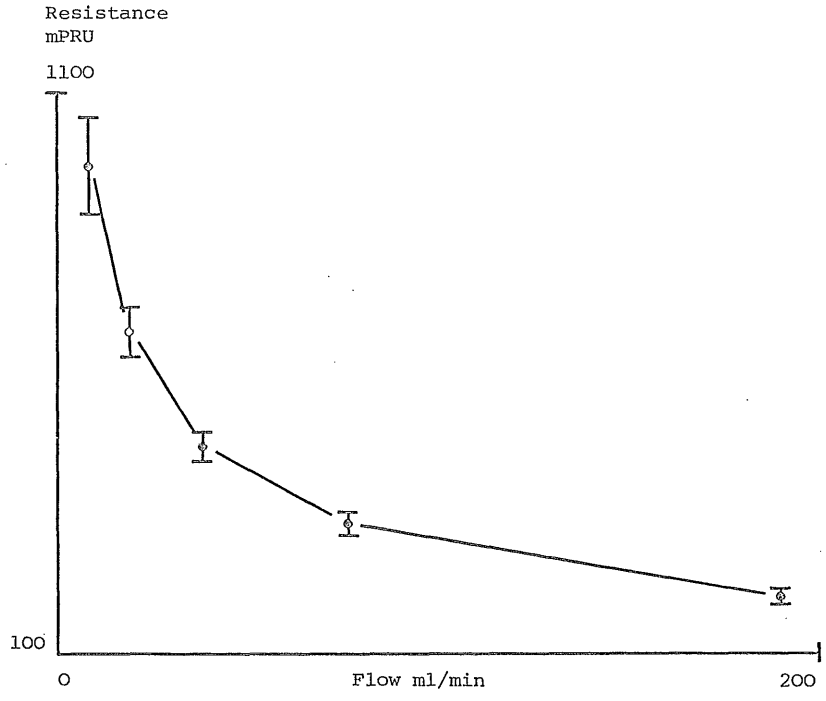
Q - Flow ml/min
AP - Arterial pressure mmHg
V - Venous pressure mmHg
Res - Resistance mPRU

Figure 6

RESISTANCE AFTER ISCHAEMIA

	Flow ml/min				
Dog	9.5	19.1	38.2	76.4	190
1	969.5	611	451.5	325.5	224.5
2	650	657.5	470	317.5	178
3	1300	855	575	393	265.5
4	1140	772.5	548.5	347.5	211
5	1425	904	581	386	226
6	1177	738.5	521	386	226
7	806.5	574	415	302	204.5
8	686.5	537.5	424	367	246.5
9	797	551	390	269.5	157
10	749.5	553	392.5	272	169

Figure 7



Mean resistance ± SE vs. flow for the ten dogs.

Resistance falls with increasing flow.

Figure 8

DISCUSSION

These results reveal a number of features in relation to the measurement of resistance. Firstly there is a non-linear relationship between flow and pressure. At low rates of flow the pressure is relatively higher than at high rates. The reason for this is unclear. When starting an infusion, many of the capillaries distally are closed and a certain amount of energy is required to open them. Until this critical closing pressure is overcome pressure rises without any flow. As flow increases the viscosity becomes relatively lower as axial streaming of the red cells increases.

In order to make a comparison between the resistance of different individuals it is desirable to measure resistance on a flat part of the resistance/flow curve. Reference to Figure 8 shows that above a flow of 76ml/min the resistance/flow relationship is approximately linear, that the curve gradient is minimised, and that it should be possible to measure resistance accurately at this level. The non-linear relationship between pressure and flow shows that it is difficult to compare the pre-ischaemia resistance values with those made after ischaemia. In this case it is possible to approximate what the resistance would have been at any given flow rate and note that after

ischaemia it is certainly lower. However if any truly valid observations are to be made regarding resistance and its comparison between individuals it clearly has to be measured at either fixed flow or fixed pressure. The work of Vetto and Dunphy (1964); Delin and Ekestrom (1965); Mundth, Darling, Moran et al (1969); and Bliss (1973) was performed at a variety of different flow rates and therefore no comparisons should have been made.

Figure 8 also shows that despite the wide variation in size between the dogs there is remarkable similarity in the resistance measured for each one. This suggests that the investigation is reproducible.

Technically the measurement of resistance was straightforward. There was no problem getting blood out for the infusion, and the measurement of pressure distal to the infusing cannula was easy using the cannula in the sidebranch.

SUMMARY

These results suggest that it should be possible to measure resistance in humans and to use it as a technique for quantifying the runoff. Resistance needs to be measured at one flow rate to make the results between individuals comparable. In the next chapter a pilot study using the technique defined in dogs has been used in humans undergoing amputation.

CHAPTER 6

AMPUTATION RESISTANCE

INTRODUCTION

The aim of the first human work on resistance measurement was to see whether the results achieved with the initial animal experiments could be reproduced in the human. It was felt that a small pilot study should be performed in humans in a situation where all the resistance measurements should be similar and where the potential risk to the patient from excessively rapid infusion could be minimised. A group of patients undergoing amputation was therefore studied.

METHOD

A group of patients undergoing lower limb amputation either above or below knee were included in this study. All the operations were performed under a general anaesthetic. Blood for infusion by the Harvard pump (Figure. 3) was withdrawn into two 50ml plastic disposable syringes. 500units of Heparin had previously been added to each of the syringes to prevent the blood from clotting. A 21 gauge cannula was placed in the

femoral vein at groin level to measure venous pressure. It was connected by a manometer line to a pressure transducer and thence to a pressure amplifier and chart recorder. Arterial pressure could not be measured by the same technique as in the initial dog experiments and therefore was measured using a 27 gauge cannula which was inserted directly into the artery under study 1cm distal to the tip of the infusing cannula. The largest cannula which could be easily inserted into the artery was used for the blood perfusion. At ankle level this was typically a 20 gauge cannula, but at knee level a 18 gauge cannula was used. The infusing cannula was connected by a manometer line to the syringes mounted on the Harvard pump. Pressure was then measured at the same series of flows that had been used in the dog experiments - namely 9.5, 19.1, 38.2, 76.4, and 190 ml/min. At each flow the infusion was maintained until the pressure was constant, and the flow was then increased. After the measurements were completed an arteriogram was performed and the amputation was completed.

PATIENTS

A series of twelve patients was studied. Their details are shown in Figure 9. One patient (No 4) had

resistance measured twice in separate vessels. Five of the patients were diabetic, seven were smokers, four were ex-smokers, and one had never smoked. Five had ulceration in the foot, seven had gangrene, four of these had both ulcers and gangrene. Three patients had had previous cerebrovascular accidents, two had had myocardial infarction, and five had coexisting hypertension. Two had had previous reconstructive surgery one profundaplasty (No 8) and one femoropopliteal bypass (No 9). Four above knee amputations and eight below knee amputations were performed. Arteriograms were available for only eight of the patients. Resistance was measured at the ankle in ten cases and above knee in three.

AMPUTATIONS

Name	Age	CVA	MI	BP^	DM	Pr	Sm	Ulc	Gan	XR
1	76	*	-	-	*	-	X	*	*	-
2	71	*	-	-	*	-	*	*	*	*
3	69	-	-	*	-	-	*	-	*	*
4	62	-	-	*	-	-	*	-	-	*
5	72	-	-	-	-	-	*	-	-	*
6	73	-	-	-	*	-	-	-	-	-
7	69	-	-	-	*	-	*	-	*	-
8	62	*	-	*	-	*	*	-	-	*
9	55	-	*	*	-	*	X	-	-	-
10	60	-	-	-	-	-	X	-	*	*
11	56	-	-	-	-	-	*	*	*	*
12	69	-	*	*	*	-	X	*	-	*

* Present
\- Absent
X - Ex smoker
DM - Diabetes mellitus
Pr - Previous surgery
XR - Xrays available

CVA - Stroke
MI - Myocardial infarct
BP^ - Hypertension
Sm - Smoker
Ulc - Ulcers
Gan - Gangrene

Figure 9

RESULTS

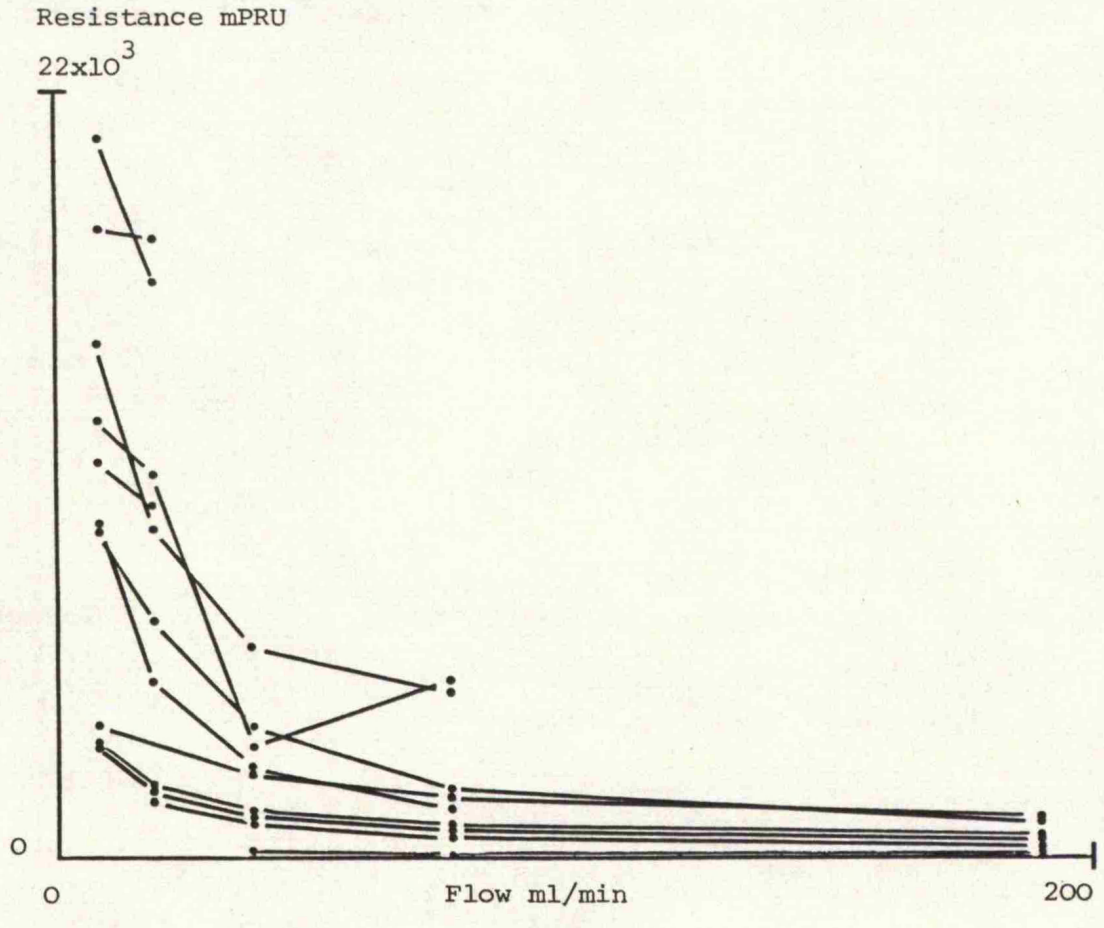
An attempt was made to measure resistance at each of the flow rates. The results achieved are shown in Table 1 in the appendix (pages B2-3), and are summarised in Figure 10. For patients 2, 3 and 4 pressures are not available at high flow rates.

AMPUTATION SUMMARY

	Flow rate ml/min				
Name	9.5	19.1	38.2	76.4	190
01	3265	2200	1465	1050	689
02	20680	16565	-	-	-
03	18020	17740	-	-	-
04	11450	10180			
	35640	-	-	-	-
05	12630	11100	3430	4830	-
06	3350	2140	1410	1050	780
07	9530	6940	4030	2070	1200
08	526	1780	1570	916	368
09	14750	9630	6280	5185	-
10	9685	5235	2830	1600	-
11	-	-	314	222	110
12	4000	-	2565	1910	1410
Mean	11960	8351	2654	2092	759
SE	2927	1922	628	617	218

Figure 10

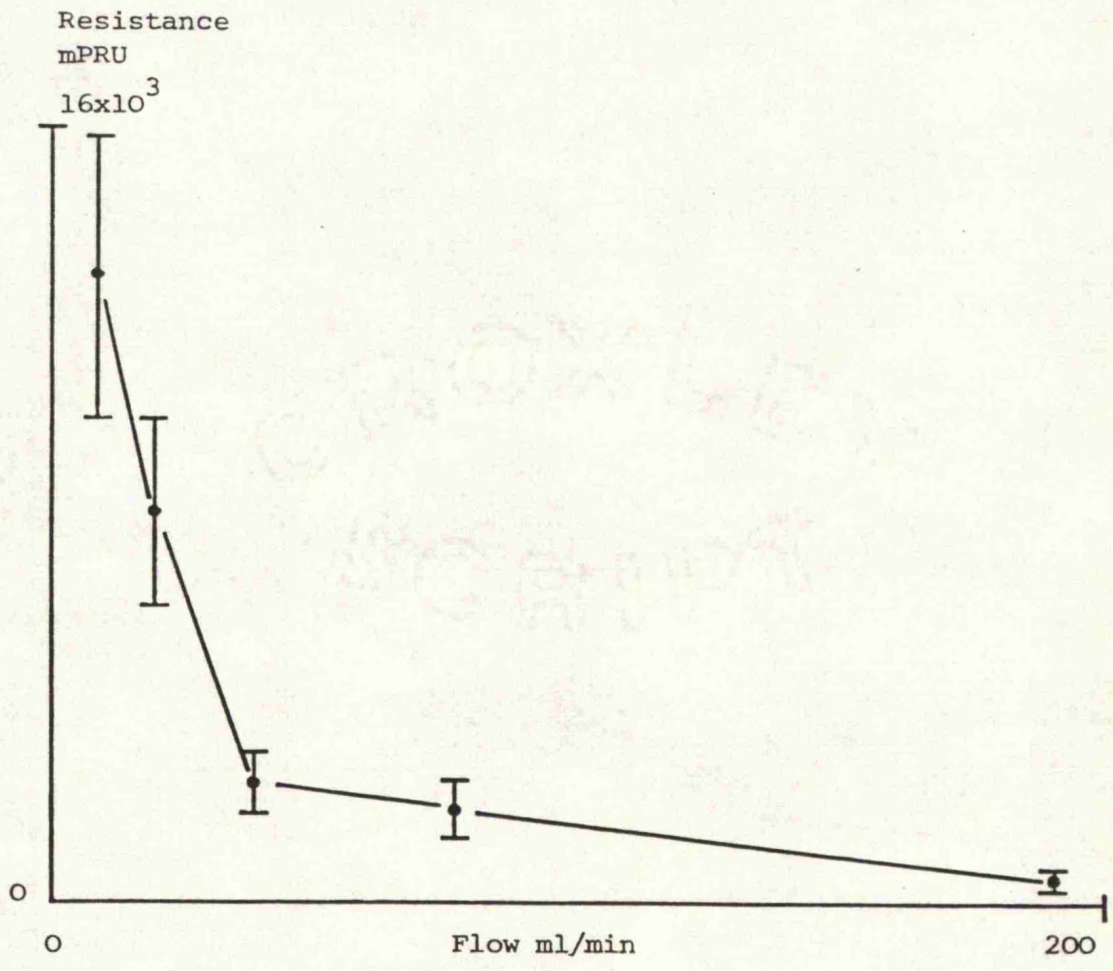
Each of these patients started with very high resistances even at the lowest flows. Single readings were unavailable for patients 9, 10, 11, and 12 for technical reasons. As in the previous experiment the



Resistance vs. flow for 12 amputees.

There is a wide range of resistance but it falls with increasing flow.

Figure 11



Mean resistance ± SE for 12 amputees.

As in the first animal experiment (Fig 9) resistance falls with increasing flow.

Figure 12

resistance fell as the flow increased in every case. This is demonstrated in Figures 11 and 12. Figure 11 plots resistance against flow for each individual and Figure 12 plots the mean and standard error of resistance against flow. The resistance measurement at 9.5 ml/min in patient 8 has been omitted from the graphs since it was obviously lower than would have been expected from the other values, and is assumed to be due to a technical error.

The results of arteriography have been included where an intraoperative arteriogram was possible and are shown in Figure 13. Each arteriogram was analysed by number of patent vessels in the calf, whether the pedal arch was intact, whether the pedal arch was present at all, and by a subjective assessment of the whole runoff. The runoff was assessed as good, moderate, poor, or terrible. In assessing the number of patent vessels in the calf, any vessel whether fully patent or patent only in small part was considered patent for the purposes of the study. A points system has been used to assess the arteriogram. One point is awarded for each occluded vessel in the calf. The overall runoff has been scored as follows : Terrible = 4, Poor = 3, Moderate = 2, Good = 1. Comparing resistance at 19.1ml/min with the arteriogram score the correlation coefficient was 0.308 P = N/S (N=6). At 38.2

ml/min and 76.4ml/min the correlation coefficient was 0.223 P = N/S (N=5) (Spearman rank correlation test). The numbers are obviously small but there was no significant correlation between runoff defined arteriographically in this way and resistance.

AMPUTATIONS

Name	Amp	Res level	Res vessel	Calf vessel	Arch OK	Arch at all	Overall runoff
1	A/K	Ank	PT	-	-	-	-
2	B/K	Ank	AT	AT	N	Y	Poor
3	B/K	Ank	PT	PT	N	Y	Terrible
4	B/K	Ank	AT PT	AT/PT	N	Y	Mod
5	A/K	A/K	Pop	AT/PT	N	Y	Mod
6	A/K	A/K	Pop	-	-	-	-
7	B/K	Ank	AT	-	-	-	-
8	B/K	Ank	AT	AT	N	Y	Poor
9	B/K	Ank	PT	-	-	-	-
10	B/K	Ank	AT	AT/PT/PN	Y	Y	Poor
11	A/K	A/K	Pop	AT/PT	Y	Y	Good
12	B/K	Ank	AT	AT	N	Y	Poor

A/K - Above knee
B/K - Below knee
Ank - Ankle level

PT - Posterior tibial artery
AT - Anterior tibial artery
PN - Peroneal artery

N No
Y Yes
- No data available

Figure 13

DISCUSSION

As in the pilot dog study the resistance has been shown to fall with increasing flow. The range of resistance values observed however was much greater in the amputation group than in the dog group. This is not surprising given the severity of the disease in the patients. In every case except one the absolute value of resistance was far in excess of the values derived for the dog. The patient with low resistance (No 11) had resistance measured at above knee level, and had excellent runoff. His gangrene was very extensive, and the aetiology of his disease was probably a mixture of Buergers disease, self inflicted damage, and frostbite, which explains why his resistance was so low compared with the rest of the group. Despite this the graphs of resistance vs. flow were of similar shape for both the amputees and the dogs suggesting that even in the presence of severe disease in the humans the distal vascular tree behaves in a similar way.

Only one set of measurements was made for each patient. None of the patients was fit, and it was felt that the anaesthetic should be kept as short as possible. The method was much more time consuming than in the dog model. This was largely due to the technical difficulty of measuring pressure in very small vessels

severely involved with atheroma. The pressure measuring cannula was hand held and therefore prone to dislodgement from the vessel. It was important to try and maintain an angle of the opening of the needle of 90 degrees to the direction of flow within the vessel. This was to avoid the error induced due to streaming.

Clearly in this series of experiments grossly unphysiological pressures were generated in the distal artery. Had the intention been to reconstruct rather than to amputate it is possible that damage might have occurred in the distal circulation. This poses a potential problem in the method with regard to application of the investigation in clinical practice.

No problems were encountered using blood as the infusing fluid from the point of view of the patient. There was no fall in systemic blood pressure when it was withdrawn. Filling the syringes with blood was however awkward. There was not access to to a large vessel and blood had to be withdrawn by stab from the femoral artery transcutaneously. Filling time was slow and not infrequently messy. The longer filling took, the cooler the blood in the syringes became and the greater the degree of separation of the blood into red cells and plasma. Clearly it might be anticipated that this will be less of a problem in patients undergoing reconstructive surgery when the groin will be open and

there will be direct access to the femoral artery.

The 50 ml plastic syringes when full of blood tended to buckle when the pump was first switched on making it difficult to get a continuous and consistent flow at the beginning of each session. This was exacerbated in the amputation experiment by the high resistance encountered. To be viable clinically, stronger or larger syringes would be required.

In the initial dog study measurement of arterial pressure distal to the infusing cannula was no problem because a sidebranch of the main artery was used. In the amputation group however needling the artery directly was probably the single most difficult problem to overcome. The needle tended either to pass through the back of the vessel or fall back into the wall of the vessel at the front. In a small vessel the potential for damage of the intima is considerable. An alternative method for measurement of pressure is required.

CONCLUSION

This pilot study of resistance measurement in humans undergoing amputation has shown that resistance measurement in human distal arteries is feasible, and that results show a similar pattern to that achieved in the healthy canine femoral artery. There were some problems with the method; firstly pressure measurement was precarious using the needle method; secondly use of blood as the infusing fluid was timeconsuming to organise; and thirdly it was possible to generate very high pressures in the artery distally.

CHAPTER 7

ANIMAL EXPERIMENT 2

Modifications to technique of resistance measurement in the animal model

Chapter 5 has shown that it is feasible to measure resistance in an animal model with good reproducibility. The pilot human study on patients undergoing amputation confirmed that the method worked satisfactorily and that the resistance/flow graphs were similar though for a wider range of values than the dogs.

The technique for measurement of resistance is however cumbersome. It adds at least another 30 minutes to the time of the procedure and for this reason alone is unlikely to be useful in clinical practice in its present form. There were four main problems.

1. It took too long to fill the syringes for the infusion. By the time they were filled the blood was cooling and separating.

2. The method for pressure measurement was unsatisfactory because of the possibility of the needle damaging the vessel, and because it was difficult to keep the needle in the vessel lumen.

3. The syringes tended to buckle when full when the

pump was first switched on.

4. The technical backup required in theatre is considerable, expensive and unlikely to be available routinely to most surgeons.

The aim of this second study on dogs was to address the above problems, and see whether it might be possible to measure resistance in any other way.

Dardik, Ibrahim, Sussman et al (1981) suggested that the 'feel' of the syringe when injecting contrast for the arteriogram gave an indication of the distal disease. They were basically using a constant pressure method for the assessment of resistance noting how long it took for the contrast to be injected. In theory there is no reason why resistance cannot be measured by a constant pressure method. To be useful the same pressure would need to be used on every occasion so that comparisons could be made. One aspect of this experiment therefore was to employ a constant pressure infusion. Flow has been measured by timing the injection of known volumes of the infusion solution. If accurate this method would provide a cheaper alternative method of measurement of resistance which might then be more available clinically.

The problem of damage to the artery by the pressure measuring needle has been studied by measuring pressure through a concentric cannula and through a

sidearm and comparing these with the stab method.

In order to try and save time in the measurement of resistance other infusion solutions have been used in addition to blood. Normal saline and Dextran are readily available and represent solutions with viscosity both higher and lower than blood.

METHOD

Four dogs were used in this study. Resistance was measured in two vessels of different calibre. As previously, the superficial femoral artery provided one runoff distally to the foot. A medium sized muscular branch of the superficial femoral artery immediately distal to the inguinal ligament was used for the other.

ANAESTHETIC

As before each animal was given a general anaesthetic. It was induced with thiopentone and was maintained with nitrous oxide, oxygen, and halothane. Ventilation was again performed by closed circuit administration of the gases through a Manley ventilator. At the end of the experiment the dogs were destroyed by the administration of a large dose of intravenous barbiturate. Fluids were given through a cannula in the

cephalic vein to maintain the central venous pressure at approximately 5mmHg. Little extra fluid was actually required because so much was given as a part of the experiments. During the procedure pulse, central venous pressure and visceral blood pressure were recorded continuously on a chart recorder. Arterial blood gases were also checked at intervals in an attempt to maintain a stable preparation. Visceral blood pressure was measured by cannulation of a branch of the superior mesenteric artery. The cannula was connected by means of a manometer line to a pressure amplifier and thence to a chart recorder. Central venous pressure was measured through a 15cm cannula inserted into the left anterior jugular vein. This too was connected via a pressure amplifier to the chart recorder. ECG was monitored by leads attached to the chest of the animal connected to an appropriate amplifier,displayed on a monitor and as pulse rate on the chart recorder. Urine output was monitored by catheterisation and collection of the urine in a graduated flask.

THE MODEL

Once anaesthetised the dog was placed on its back on the operating table and its legs were strapped out. As before sandbags were placed along the trunk to

prevent it from twisting over and the warming blanket was set to 38 degrees centigrade. A single incision was made extending from 7cm below the xiphisternum in the midline down the midline to the the point marked by a line perpendicular to the inguinal ligament passing through the femoral artery. The incision was then taken along this line and into the upper part of the thigh. The hindlimb was then rendered ischaemic by the technique of Johansen and Bernstein (1979). However proximally the main trunk of the external iliac and superficial femoral arteries were left unligated. Distally ligation was carried approximately 12cm down the thigh to just beyond the origin of the saphenous artery. A single posterior muscular branch, which was consistently present and positioned about 1cm distal to the inguinal ligament was left unligated. This provided one of the two runoffs down which resistance would be measured. A sidebranch of this muscular branch was cannulated with a 20 gauge cannula. This was for the 'needle' stab pressure measurement. The cannula was connected to the chart recorder by a manometer line, pressure transducer and pressure amplifier. Distally in the thigh the saphenous artery was similarly cannulated and connected to the chart recorder. All branches in the thigh proximal to the saphenous artery were ligated. The second runoff was the main superficial femoral artery

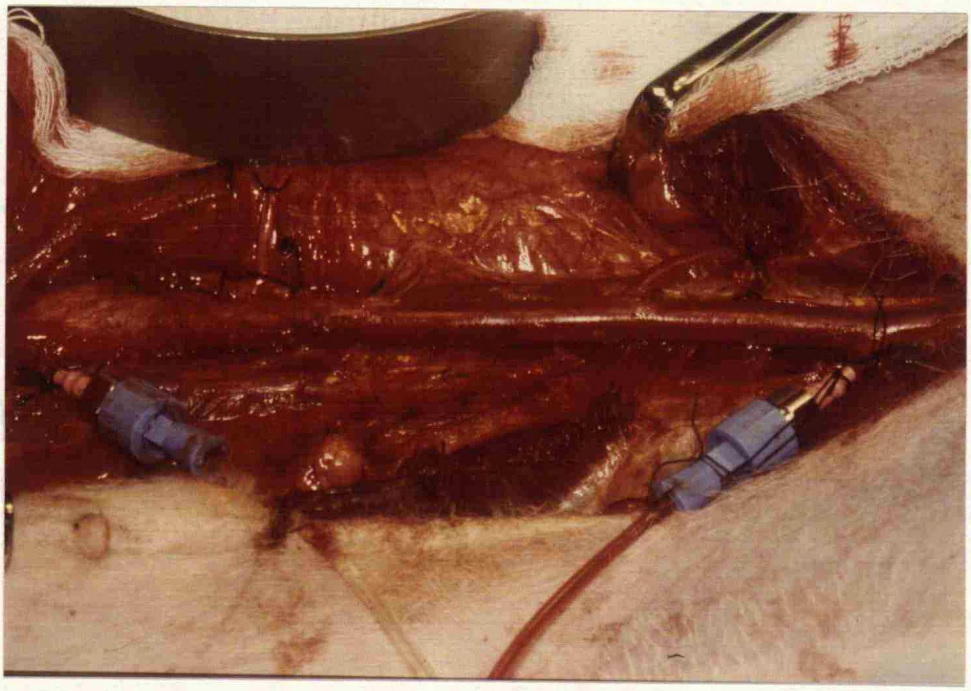


Figure 14.

Twenty gauge cannulae have been placed in the femoral artery at inguinal ligament and midthigh position.

whose pressure was being measured by the cannula in the saphenous artery as shown in Figure 14.

The infusion was performed by the Harvard pump but the 50ml plastic disposable syringes were exchanged for two 100ml glass syringes (Fisons). The syringes were not heparinised. Instead the dog was heparinised systemically. During the course of the experiment the syringes were refilled with blood approximately twelve times. It was felt that there would be difficulties with control of blood clotting towards the end of the experiment if the syringes were heparinised each time they were refilled. Each dog was therefore given heparin by continuous infusion through a cannula sited in the right anterior jugular vein. The dose given was 200 units by bolus injection at the start of the experiment followed by an infusion of 500 units/hour. Using this regimen, which was derived empirically on a weight basis from the human infusion dose of 30,000 units/day, there was no obvious problem clinically with either over or under anticoagulation.

The infusion cannula was also altered to accommodate pressure measurement by concentric and sidearm techniques. The cannula used for the infusion was a 14 gauge Cathlon type. Connected immediately to it was a 'Y' adaptor (Vygon) with Luer type connectors. One limb of the 'Y' was closed with a plastic cap, in the

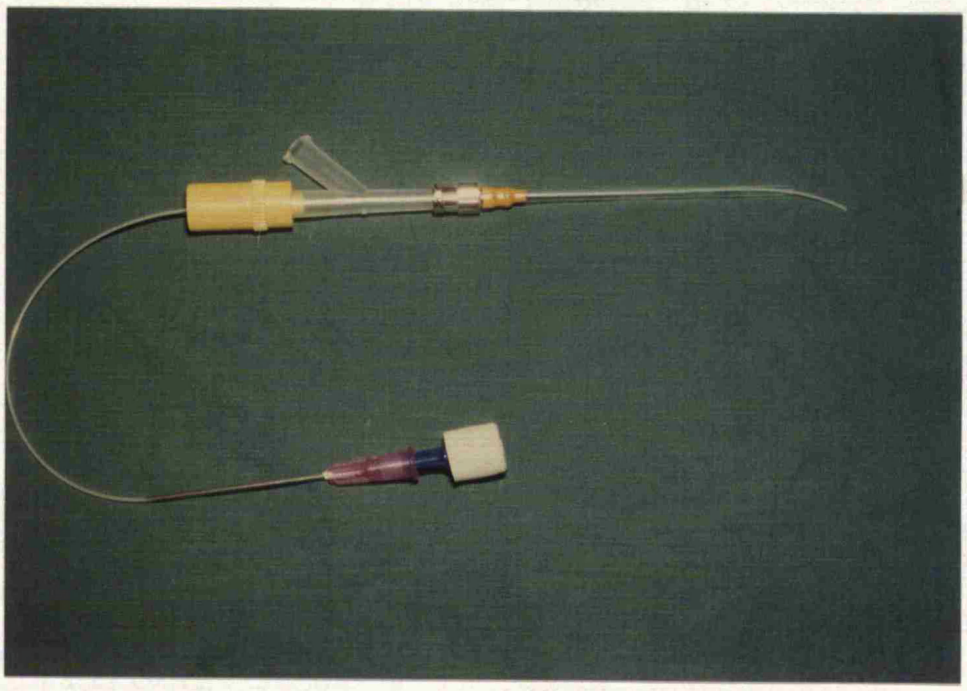


Figure 15

The completed concentric cannula ready for use.

centre of which was a rubber diaphragm. Through this diaphragm was placed a 20 gauge epidural catheter. The catheter passed down the main infusing cannula and was cut to length so that 1.5cm of it projected beyond the tip of the main cannula (Figure 15). A 14 gauge cannula was used to accommodate the epidural catheter without excessive narrowing of the main channel. The other limb of the 'Y' was connected directly to a 3-way tap. One limb of the 3-way tap was connected to the syringes on the harvard pump with a manometer line. The other limb, the sidearm pressure, was connected to a pressure transducer and thence to the chart recorder. Once assembled the cannula was inserted into the superficial femoral artery approximately midway between the two runoffs and facing distally.

MEASUREMENT

The experiment was undertaken in three parts. When each part had been completed once, the whole routine was repeated.

1. In order to use the sidearm method for measuring pressure it is necessary to know the resistance of the cannula distal to it. Ideally it should be constant. The resistance of the infusing cannula was measured by connecting up the component parts of the cannula and connecting it to a syringe filled with blood. The pump was then set to 45ml/min and run with the cannula open to the air. Pressure was measured in the sidearm. The resistance was then calculated from this pressure and the preset flow from the pump. The resistance was measured at three further flow rates slightly different from the previous experiments; 83, 117, and 153 ml/min. Having completed the resistance measurement with blood the procedure was repeated using first saline and then Dextran.

2. Resistance was measured as in the initial dog study. Blood was infused into the superficial femoral artery at four flow rates; 45, 83, 117, and 153 ml/min. Firstly the distal runoff was clamped so that resistance

was measured in the proximal runoff. Then when this had been completed at each of the flow rates the proximal runoff was clamped and the measurements were repeated in the distal runoff. This procedure was then performed for saline and Dextran. All of the solutions were maintained at 38 degrees centigrade.

3. All measurements of resistance were made by measuring pressure simultaneously by the 'stab', concentric and sidearm techniques. The accuracy of the sidearm and concentric cannula techniques could then be compared with the 'Stab' technique.

4. Resistance was measured using a constant pressure infusion. A hand held 100ml glass syringe filled with blood was connected to the infusing cannula. Infusion was commenced and recording of the flow was begun when a steady pressure had been achieved in the 'stab' pressure line. A timed infusion of known volume was then performed so that the flow could be calculated. At least three recordings of resistance were made in this way in each of the runoffs and with each of the solutions. An attempt was made to use the same pressures each time so that the results could be compared.

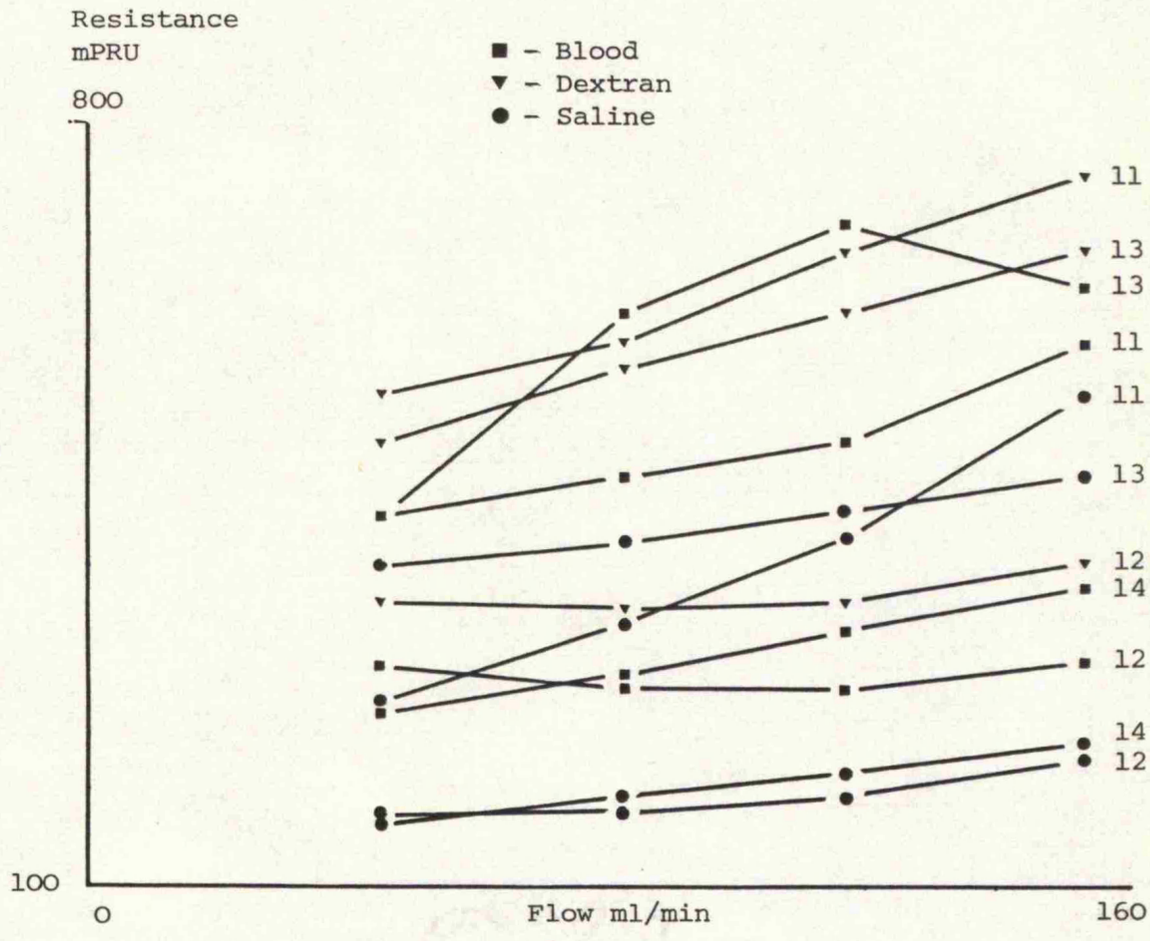
Between measurements the superficial femoral

artery was unclamped so that blood could come into the limb through the external iliac artery and prevent the limb from becoming ischaemic. This first set of measurements were therefore made 'at rest'. After completion of the first set of measurements, the external iliac artery was then clamped permanently. After an hour all the measurements were repeated with the assumption that the peripheral vasculature was maximally dilated due to the ischaemic interval.

RESULTS

1. CANNULA RESISTANCE

The resistance between the sidearm and the tip of the infusing cannula has been calculated for each of the infusing solutions at four flow rates - 45, 83, 117, and 153ml/min. The results are shown in Table 1 in the Appendix (page C3) and Figure 16. For each cannula and for each solution except Dog 13 (blood) there was a small steady parallel rise in resistance with increasing flow. The absolute values were greatest for Dextran and smallest for saline. Combining the resistances at all four flow rates and allowing for the fact that there was a wide range of resistances, resistance measured with blood was significantly greater than saline in Dog 12 ($p<0.05$), and Dog 14 ($p<0.05$). Similarly Dextran resistance was greater than saline in Dog 12 ($p<0.05$) and Dog 13 ($p<0.05$). In one case Dextran resistance was significantly greater than blood - Dog 12 ($P<0.05$). There were striking differences between dogs however with a range of resistance at 45ml/min of between 266mPRU and 444mPRU for blood, 166mPRU to 400mPRU for saline and 366mPRU to 555mPRU for Dextran. These differences were repeated at each of the flow rates.



Cannula resistance for the four dogs has been plotted against flow for each of the infusion solutions. Resistance increases with flow, and with the viscosity of the infusing fluid. There is wide variation.

Figure 16

DISCUSSION

The resistance of the cannula was 100-700mPRU which indicated that despite using a large cannula its resistance was still moderately high.

To be useful in practice a sidearm technique of pressure measurement requires that the resistance of the cannula between the sidearm and the patient is always the same and preferably minimal. If it is not then the resistance of the cannula must be calculated each time it is used. These results show a wide variation in resistance measured for each of the solutions and that the resistance actually increases slightly with increasing flow. It is very unlikely that in clinical practice it would be possible to calibrate a cannula each time resistance was measured. The differences in resistance measured are presumably due to small differences in the diameter of the 14 gauge cannula and the epidural catheter down the middle. Differences in resistance with blood could be accounted for by differences in haematocrit but this is not the case for the saline or Dextran. The resistance of the cannula could have been reduced by removing the concentric epidural catheter. Measurements were not made under these circumstances, but irrespective of this possibility the cannula would still have presented some

resistance. On the basis of these observations it would seem that a sidearm measurement of pressure is not viable, and that the same changes occur with each of the infusion solutions.

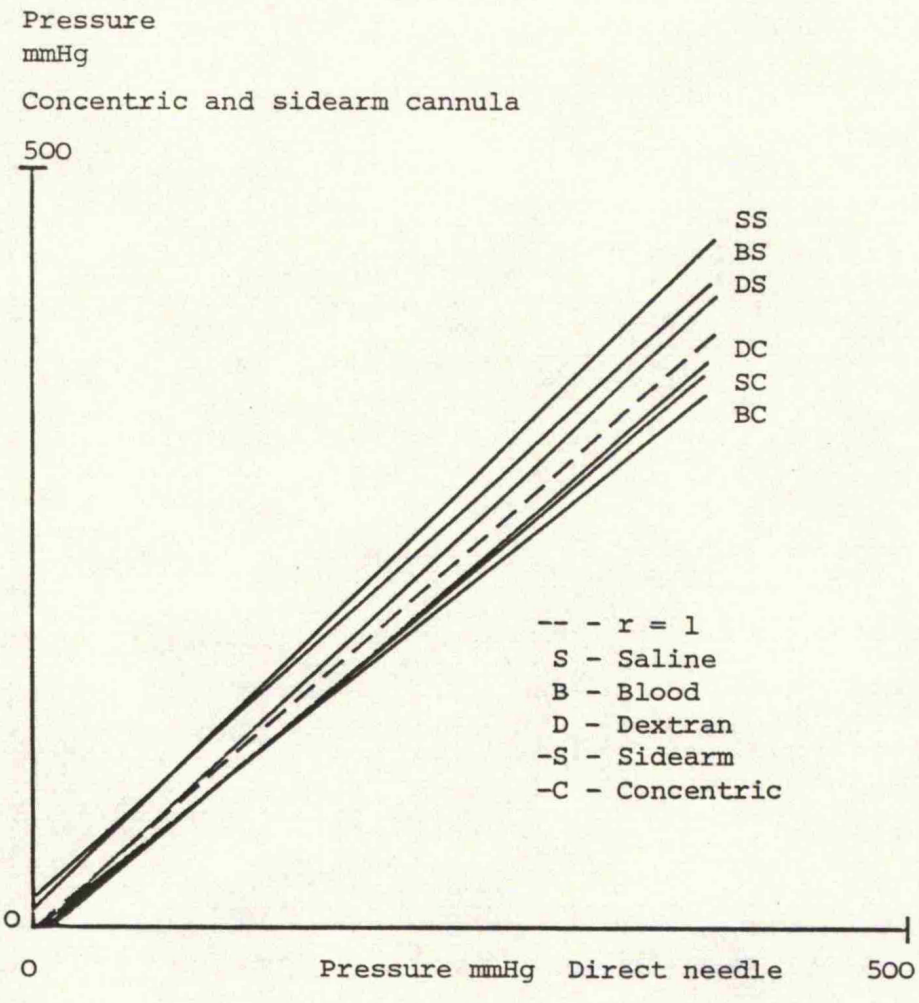
2.SIDEARM CONCENTRIC AND 'STAB' RESISTANCE

In each of the experiments pressure was measured simultaneously by the three methods. Results of these simultaneous pressure measurements are shown in Tables 2,3, and 4 in the appendix (pages C4-6). There were 63 sets of measurements for the blood, 59 for saline and 61 for Dextran. Mean pressure measured by the sidearm was significantly greater than that measured by the 'stab' for all of the solutions; blood $t=2.63$ $p<0.005$; saline $t=2.148$ $p<0.05$; and Dextran $t=2.699$ $p<0.005$ (Paired t test). There was no significant difference between the mean pressures measured by the concentric cannula and 'stab'. There was excellent correlation between concentric pressure and 'stab' pressure.

Solution	r	Int	Slope
Blood	0.9845	8.24	0.89
Saline	0.9976	1.289	0.996
Dextran	0.991	2.29	0.948

Concentric vs. 'stab' pressure

However when comparing the sidearm with the 'stab' the correlation was much less good.



Concentric and sidearm pressure vs. 'stab' pressure. The best correlation is found between the concentric and 'stab' methods.

Figure 17

Solution	r	Int	Slope
Blood	0.945	30.7	1.013
Saline	0.911	13.8	1.094
Dextran	0.943	23.53	1.094

Sidearm vs.'stab' resistance

The above results are shown in graph form in Figure 17.

When combining the measurements from the three solutions together the results are similar.

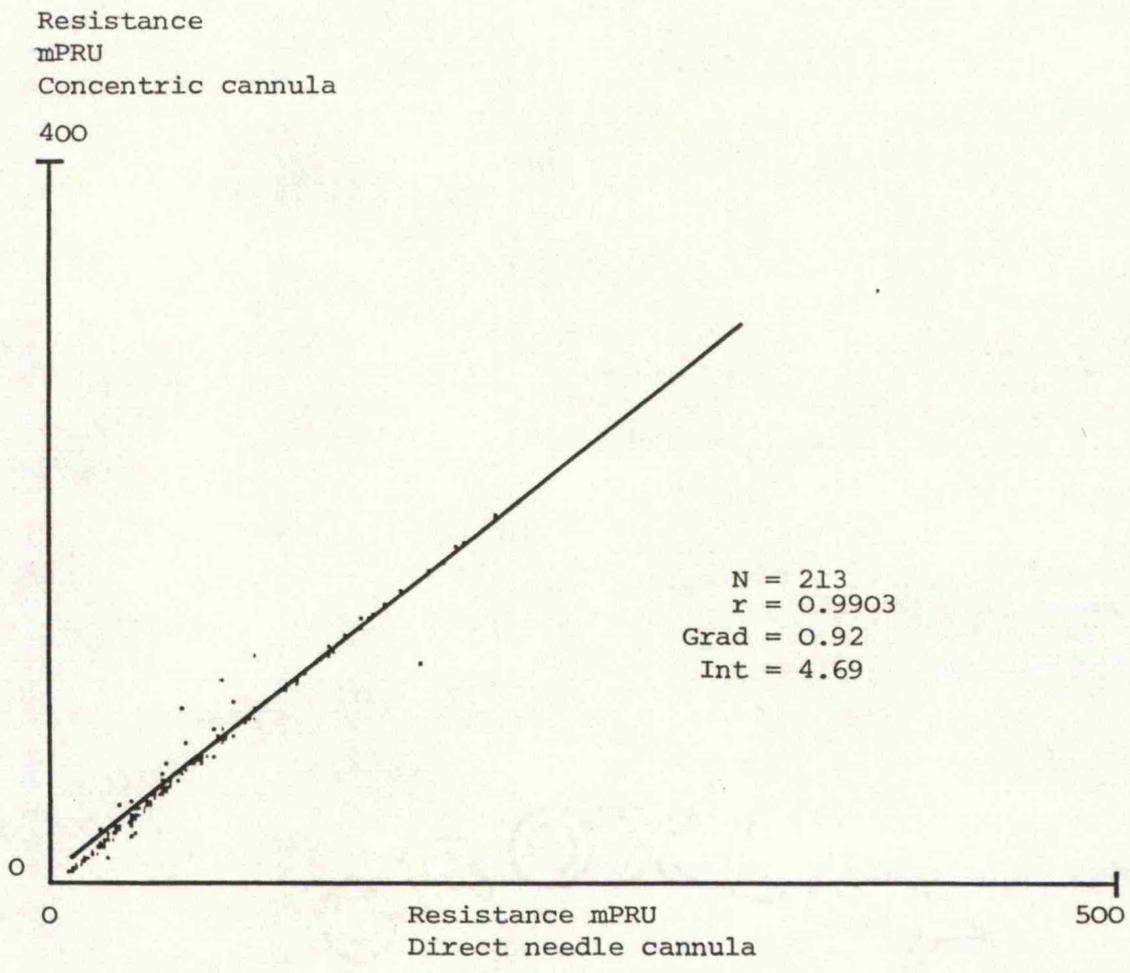
Concentric vs. Stab

r	Int	Slope
0.9903	4.69	0.92

Sidearm vs. stab

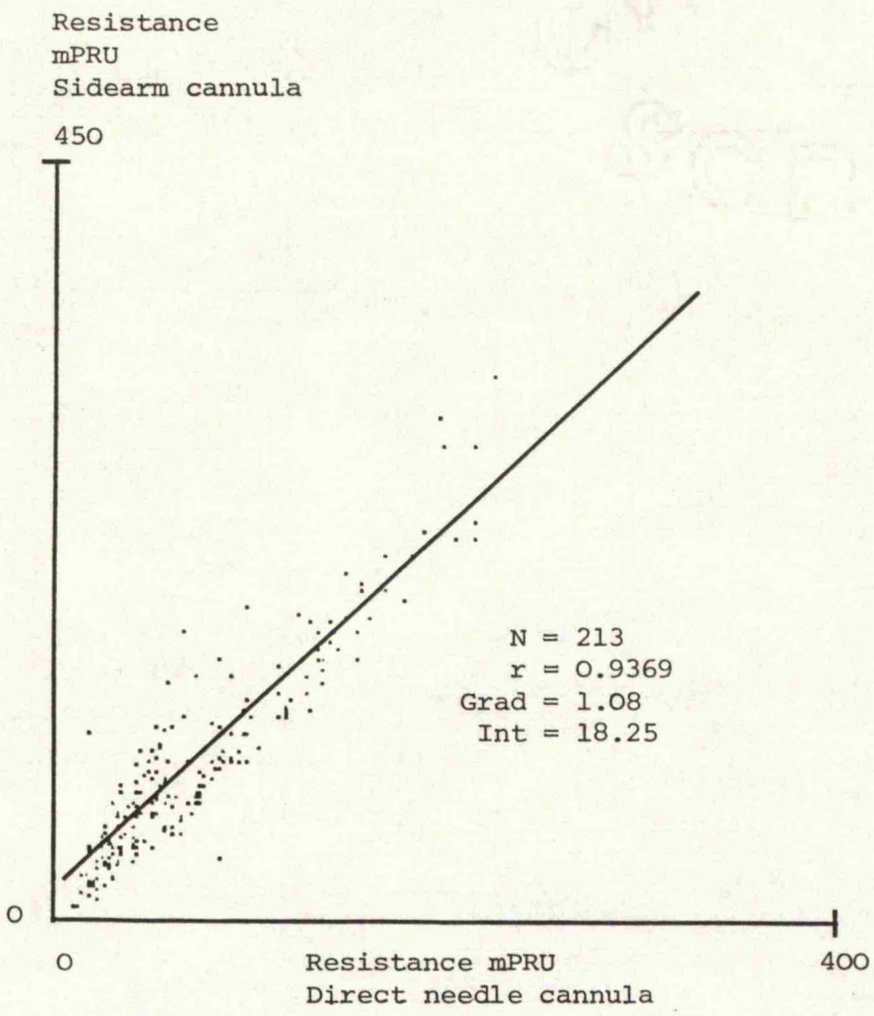
r	Int	Slope
0.9369	18.25	1.08

These results are shown in Figures 18 and 19. The difference between the means is highly significant for the sidearm vs. 'stab'; t=4.27 p=0.0001.



There is good correlation between the concentric pressure and the 'stab' pressure.

Figure 18



There is poor correlation between the sidearm pressure and the 'stab' pressure.

Figure 19

DISCUSSION

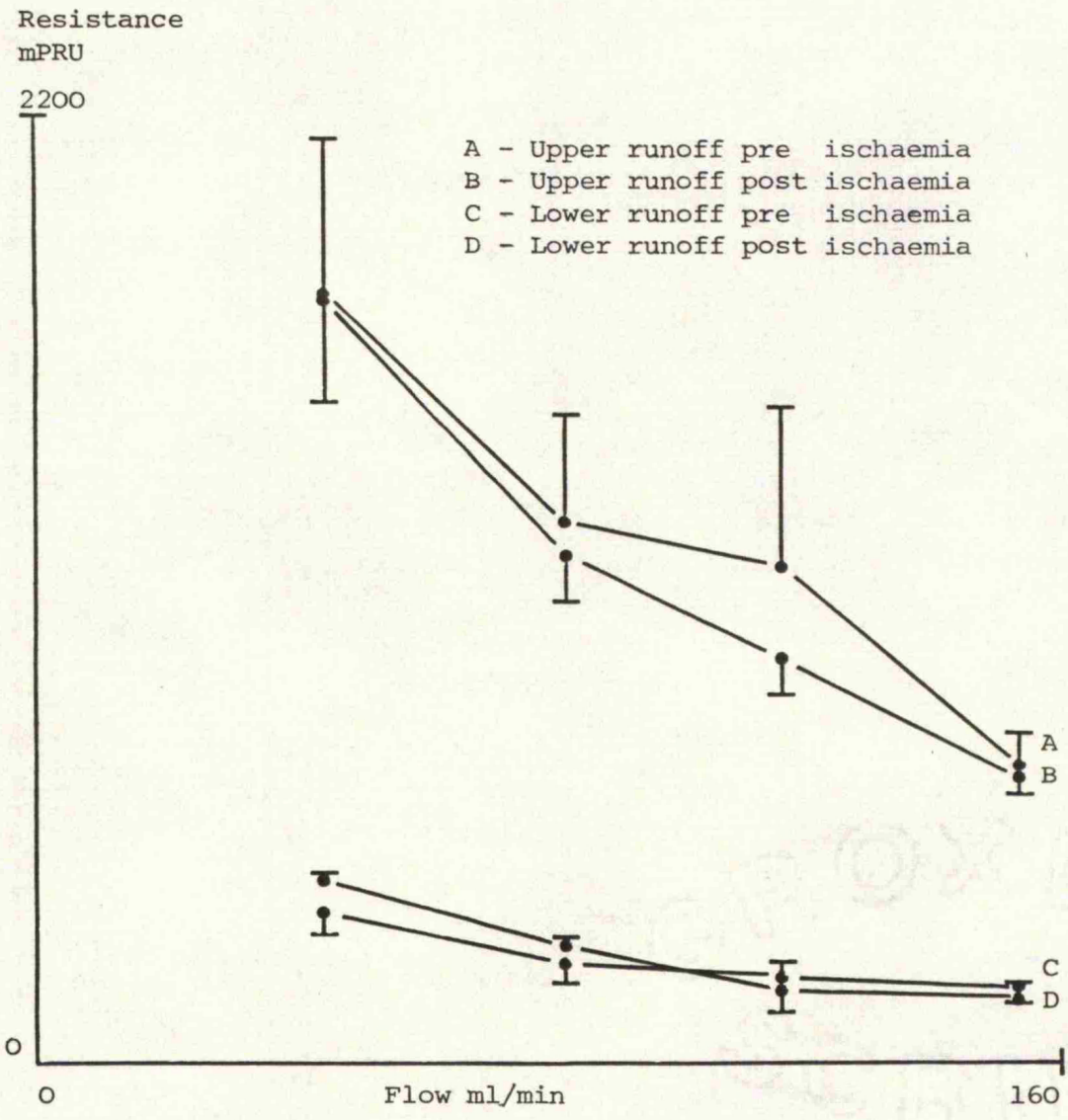
The important finding from these results is that there is no difference between the concentric and 'stab' pressure measurements but that both of these are significantly different from the sidearm measurement. This means that in clinical practice it will be acceptable to use a concentric cannula for pressure measurement which will make the procedure for patients much quicker, and easier. There were no technical problems in the dog using the concentric cannula, and provided that the human popliteal artery is sufficiently large there should be no problems in the human. When studying an artery at ankle level a size 14 cannula may be too large and under these circumstances it will be necessary to continue with direct needling of the vessel with a 27 gauge cannula to measure pressure and to infuse through a smaller cannula.

3. RESISTANCE - BLOOD SALINE AND DEXTRAN

In this and subsequent experiments pressure recorded from the concentric cannula has been used to calculate the resistance. Raw data of resistance measured is shown in Tables 5, 6, and 7 in the Appendix (pages C7-9). The upper runoff has a higher resistance than the lower runoff for all solutions. If the results for each flow rate from each of the dogs are grouped together then for Dextran, the differences in resistance between upper and lower runoffs before ischaemia are significant as follows: upper runoff $p<0.05$ at 45, 83, and 117ml/min (there were no measurements made at 153 ml/min for dogs 11 and 12). For saline and blood the differences are also significant at 45, 83, and 117ml/min for both the upper and lower runoffs ($p<0.05$).

In each case for the smaller upper runoff the resistance falls as the flow increases as in the previous experiment. In the larger runoff however the resistance remained approximately the same over the range of flows tested. These results are shown in Figures 20, 21, and 22, where mean resistance $\pm$ standard error are plotted against flow.

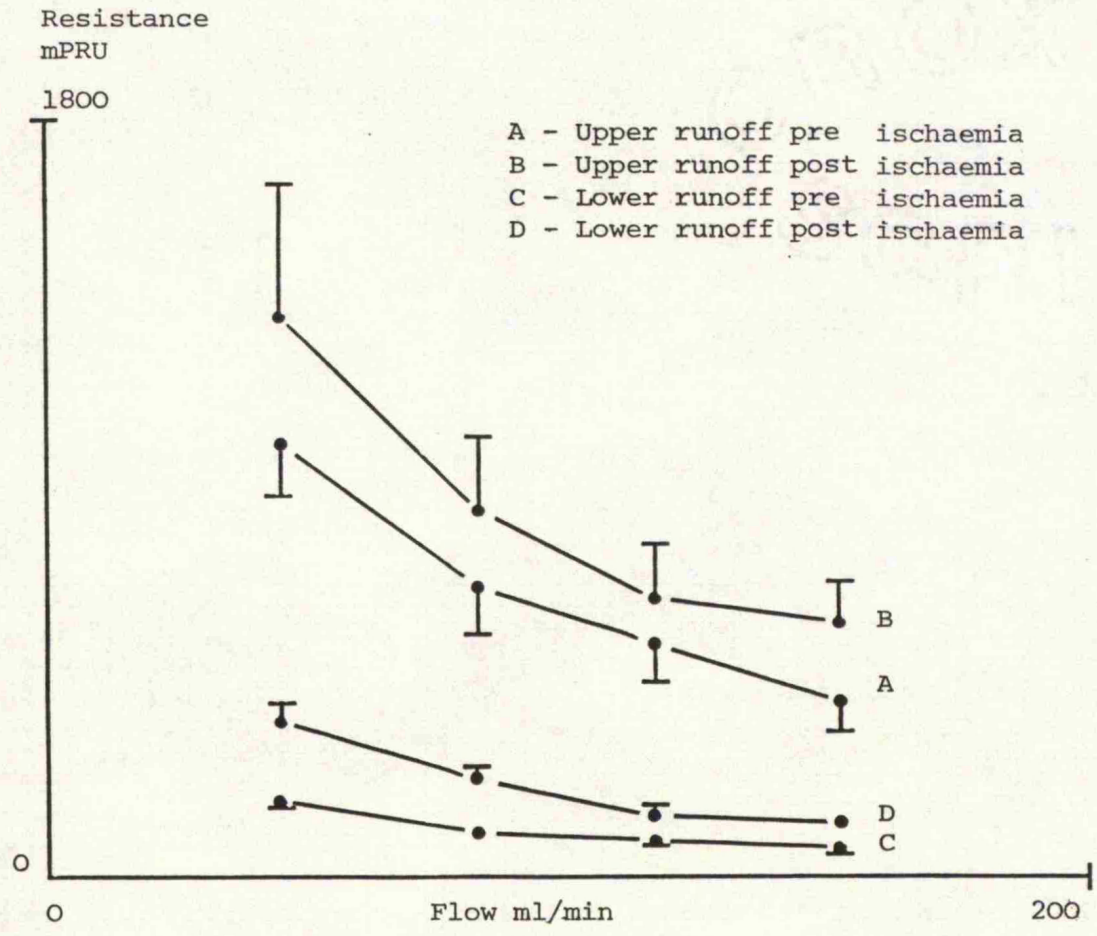
The resistances measured after the ligation of the external iliac artery are shown on the same figures. For both runoffs the shape of the resistance/flow curve



Pumped infusion of blood

Resistance vs. flow for blood. Resistance is higher in the smaller runoff and falls in both with increasing flow. Ischaemia does not significantly alter resistance.

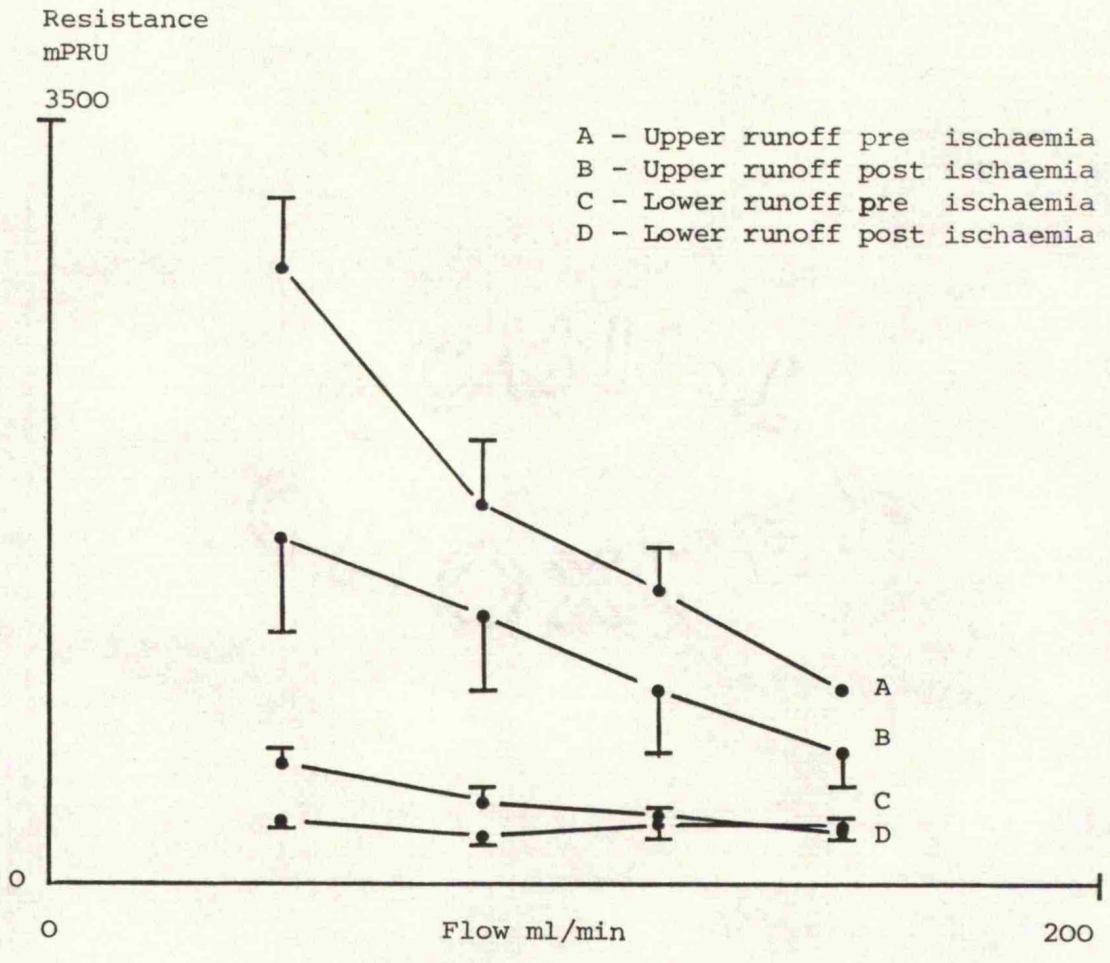
Figure 20



Pumped infusion of saline

Resistance vs. flow for saline. Resistance is higher in the smaller runoff and falls in both with increasing flow.

Figure 21



Pumped infusion of Dextran

Resistance vs. flow for Dextran. Resistance is higher in the smaller upper runoff and falls with increasing flow. The resistane was lower after ischaemia in the upper runoff.

Figure 22

is much the same and for blood and Dextran the resistance is slightly lower. For saline there was a small rise in resistance after the introduction of ischaemia for both runoffs. From the graphs it can be seen that the best separation of resistance between the two runoffs is provided by the blood, although there were also statistically significant differences in the case of both saline and Dextran.

Resistance was measured before ischaemia in the upper runoff at 83ml/min combining the measurements from each of the dogs. Resistance measured with Dextran was higher than for blood (mean 1768 mPRU SE 282 vs. 1483 mPRU SE 143) but not significantly so. There were significant differences between blood and saline (mean 1483 mPRU SE 143 vs. 701 mPRU SE 106; $p<0.05$) and between Dextran and saline (mean 1768 mPRU SE 282 vs. 701 mPRU SE 106; $p<0.05$). Similar results are found for the lower runoff before ischaemia ($p<0.05$) but again the differences between blood and Dextran were not significant. After the introduction of ischaemia there were no significant differences for either runoff, but for the larger runoff the resistance measured with Dextran was again highest and that measured by saline the lowest.

Considering resistance at any one flow rate then for the smaller upper runoff the introduction of

ischaemia only reduced resistance for Dextran but for saline and blood there was no significant difference. For the larger runoff introduction of ischaemia made very little difference. Papaverine has previously been shown to be a more potent vasodilator than induction of ischaemia by tourniquet (Dedichen and Myhre 1975) but use of papaverine in this experiment would not have been possible because of the large numbers of observations to be made.

DISCUSSION

From this experiment it can be seen that each of the solutions can separate the two runoffs from each other. Looking at the graphs suggests that the Dextran and blood produce a wider separation than the saline. This may prove important in clinical practice where as wide a separation as possible would be useful.

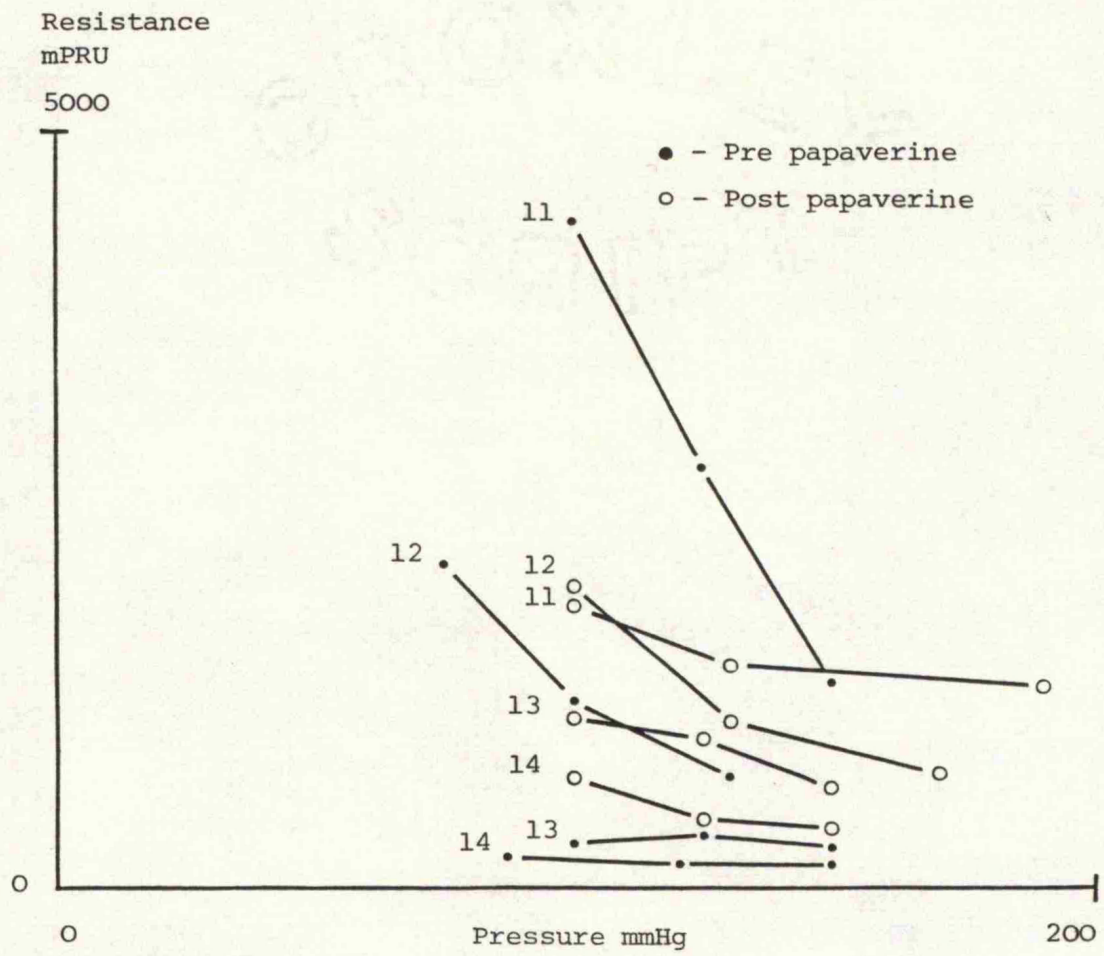
It is surprising that resistance does not fall with increasing flow for the physically larger lower runoff as it does for the smaller runoff. It may be that the pressures generated by the available flow in the larger runoff are in fact unphysiologically low and this may explain the differences.

There seems to have been no significant fall in resistance following ligation of the external iliac artery in either of the runoffs, and in fact for saline the resistance actually rose for both runoffs. This is most obvious in the larger runoff and could be explained on the basis of resistance measurement at unphysiologically low flow rates. Also it is possible that despite trying to avoid ischaemia during the early part of the experiment the runoffs were in fact ischaemic and already vasodilated. Alternatively the saline or Dextran may have affected resistance directly, or the dogs may have been becoming haemodynamically unstable after a long anaesthetic.

The results of using the different infusing solutions were predictable. Dextran being more viscous than blood or saline produced the highest resistance values. Saline being the least viscous produced the lowest resistances. The important property of the infusing solution is that it provides the widest possible separation by resistance of different runoffs. Because of its low viscosity saline is least suitable in this respect. The dogs tolerated rapid infusion of Dextran poorly with the onset of muscle fasciculation in the leg distally. Whilst this is unlikely to occur in humans the additional advantages of Dextran over blood would not justify its further use.

4. CONSTANT PRESSURE RESISTANCE MEASUREMENT

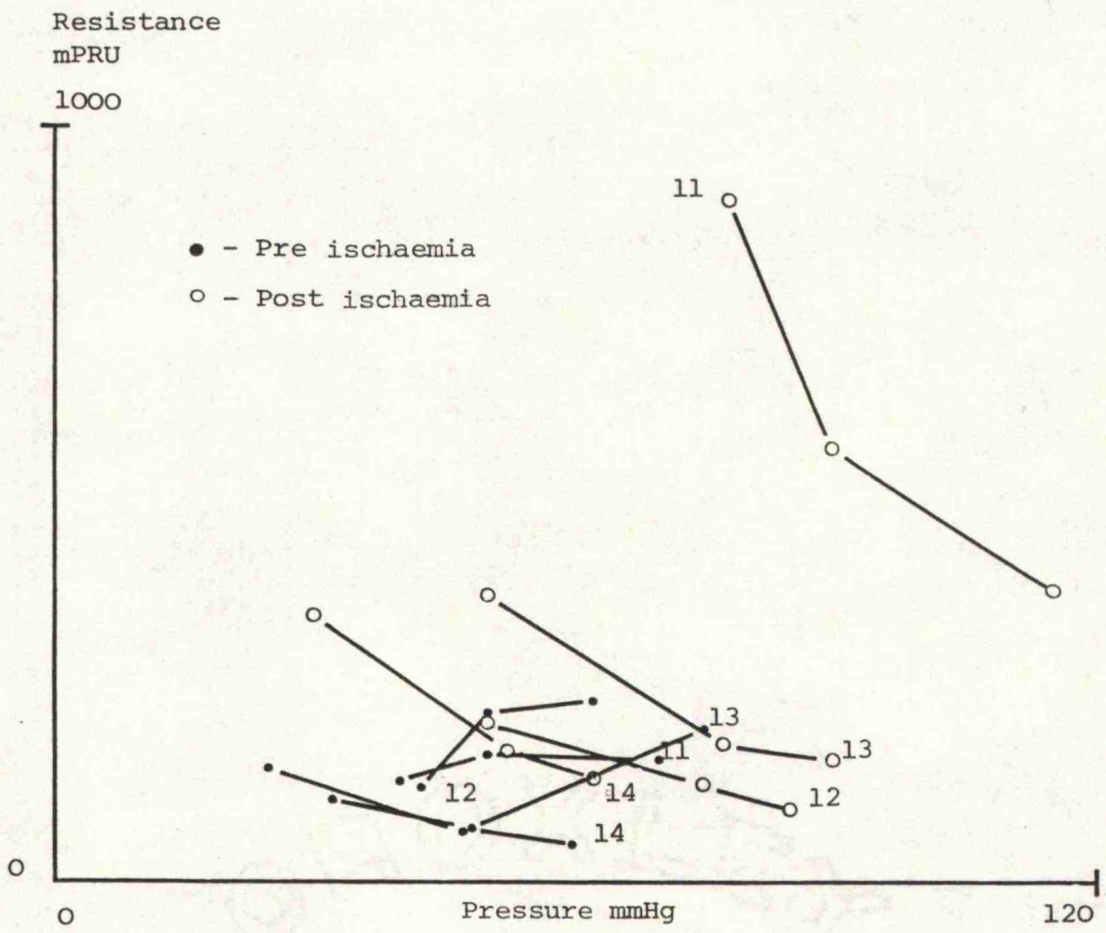
Results of constant pressure measurements are shown in Tables 8,9, and 10 in the appendix (pages C10-12). The results are displayed graphically in Figures 23, 24, 25, 26, 27, and 28. An attempt was made to measure resistance at the same pressure for each dog and for both runoffs. For the lower runoff with the larger lumen however it was impossible with the handheld syringe to generate a pressure above 78mmHg except in 12 out of 72 cases (8 with Dextran). Flows at 75mm Hg were typically in excess of 300ml/min (range 150-720 ml/min). Similarly for the smaller upper runoff it was very difficult to get the pressure below 100mmHg (only 8/72 cases). Flow at 100 mmHg was typically 75ml/min (range 21-225 ml/min). From the Figures 24, 26, and 28 it is clear that unlike the constant flow infusions there was no clear pattern for the lower runoff in the relationship between pressure and resistance. For the upper runoff however where the pressures generated were more uniform the characteristic pattern of falling resistance with increasing pressure was observed. Comparisons involving pooling of data of all four dogs was not possible because resistance was measured at a selection of different pressures. As before resistance was higher when calculated for blood and Dextran than



Manual infusion of blood - upper runoff

Resistance falls with increasing pressure. Ischaemia does not significantly alter resistance.

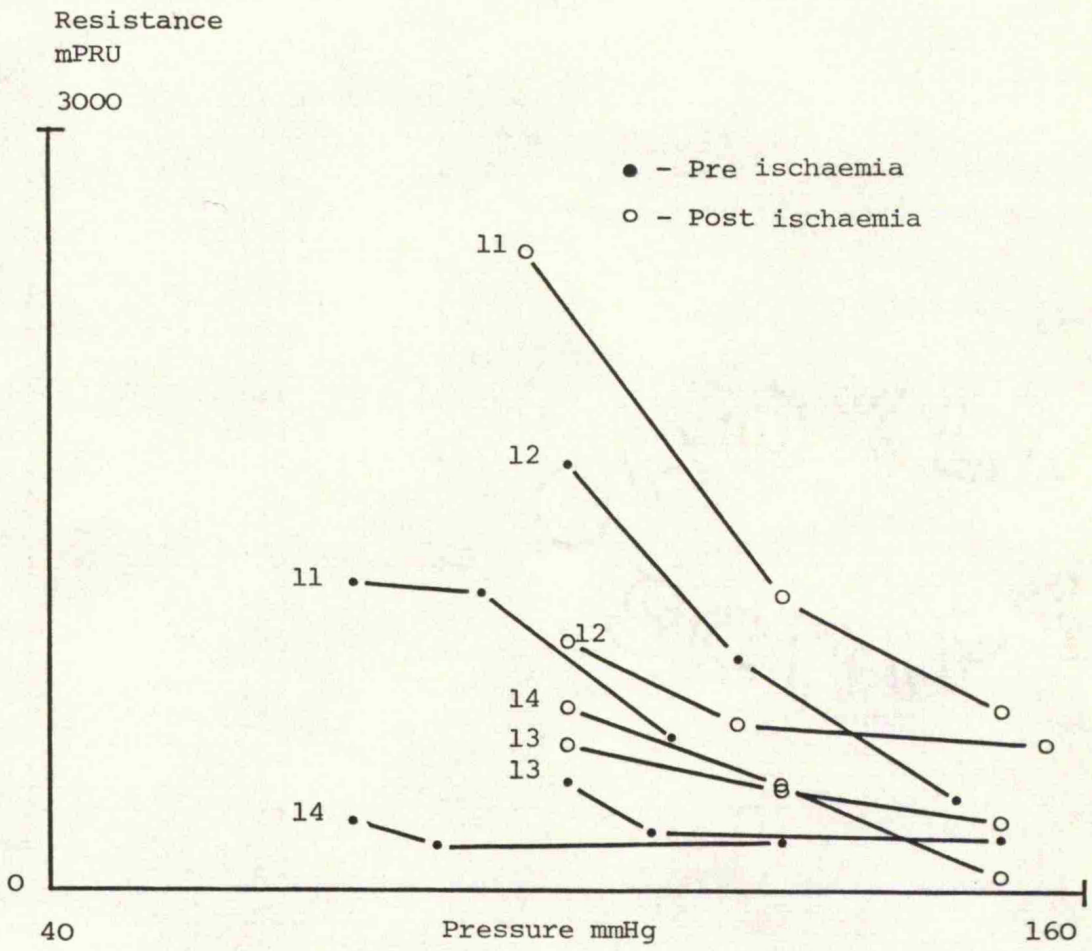
Figure 23



Manual infusion of blood - Lower runoff

Resistance was very low in each of the dogs. There was no significant relationship between pressure and resistance in this runoff.

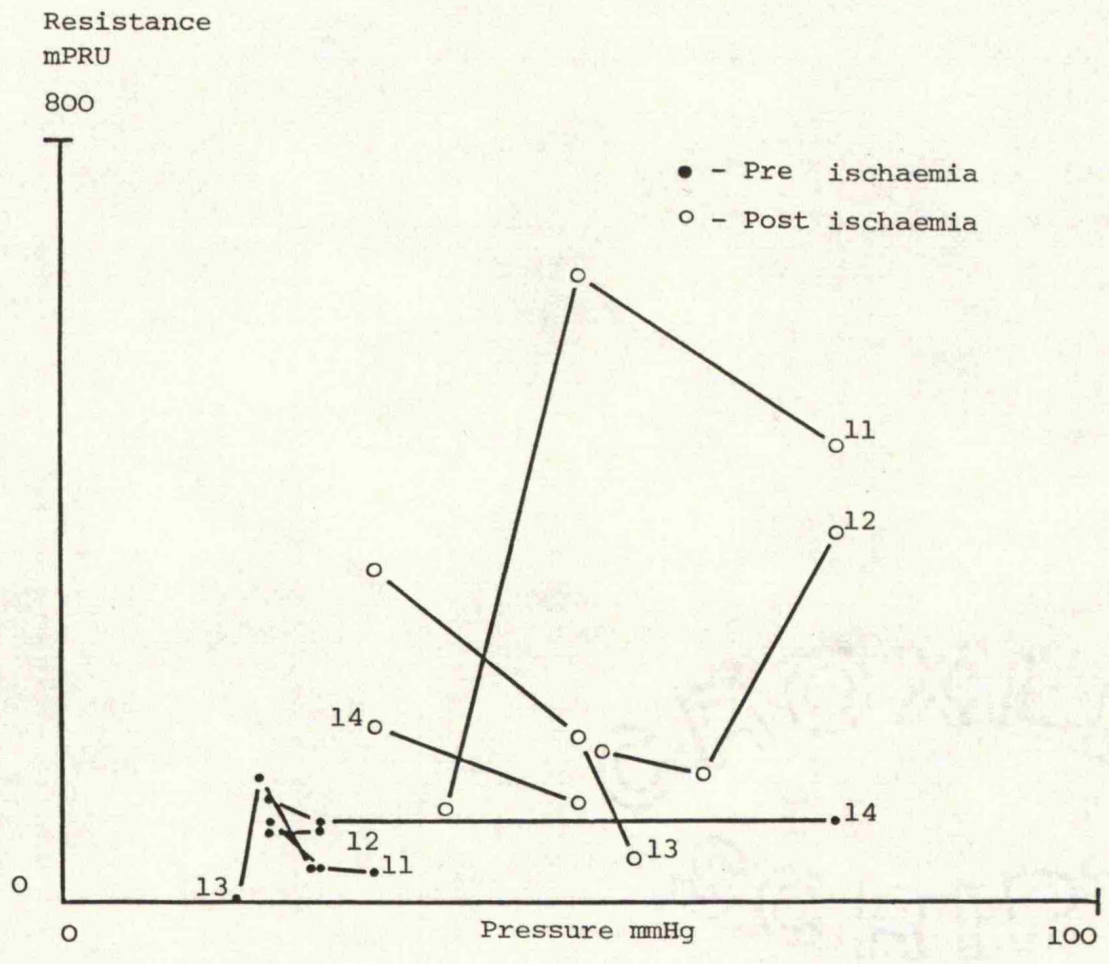
Figure 24



Manual infusion of saline - Upper runoff

Resistance falls with increasing pressure. The effects of ischaemia are unpredictable.

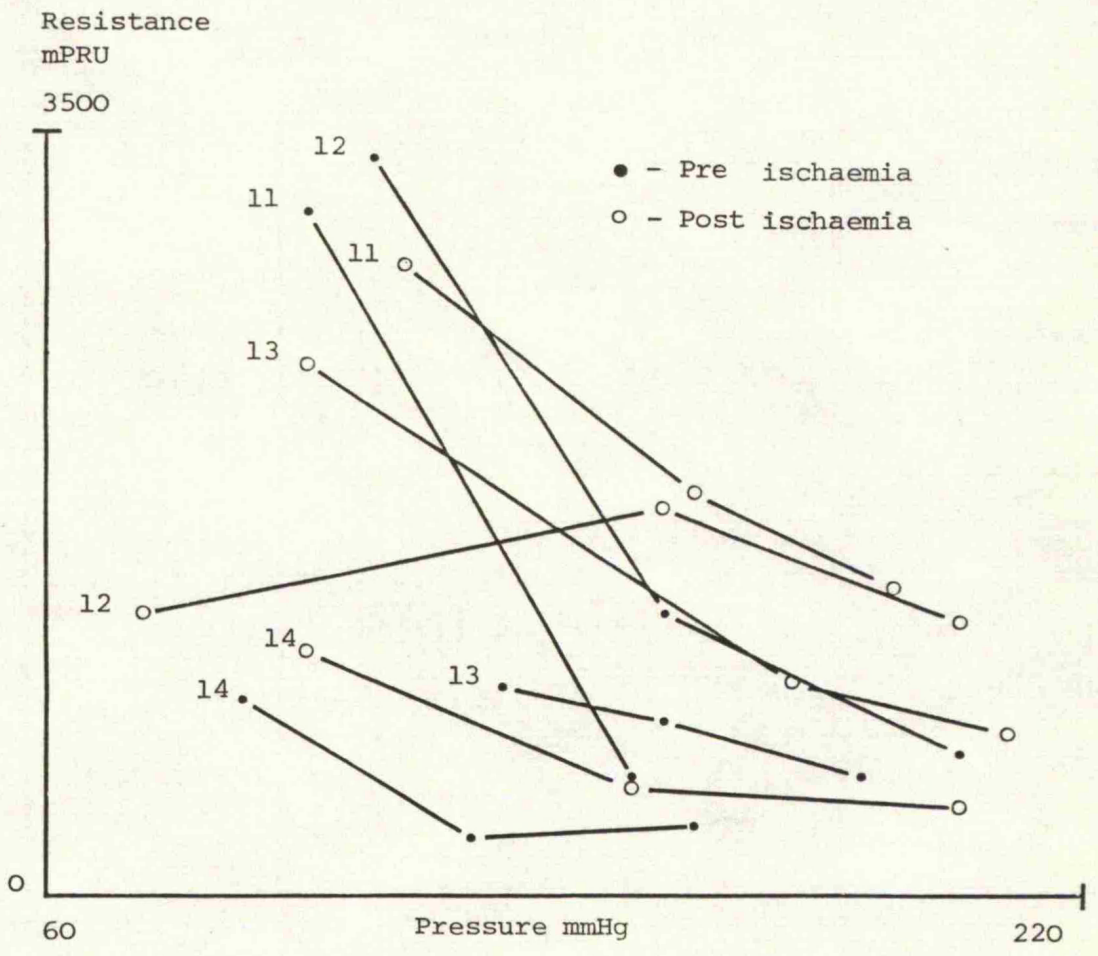
Figure 25



Manual infusion of saline - Lower runoff

There was no relationship between pressure and resistance. A combination of low distal resistance and the low viscosity of saline may account for this.

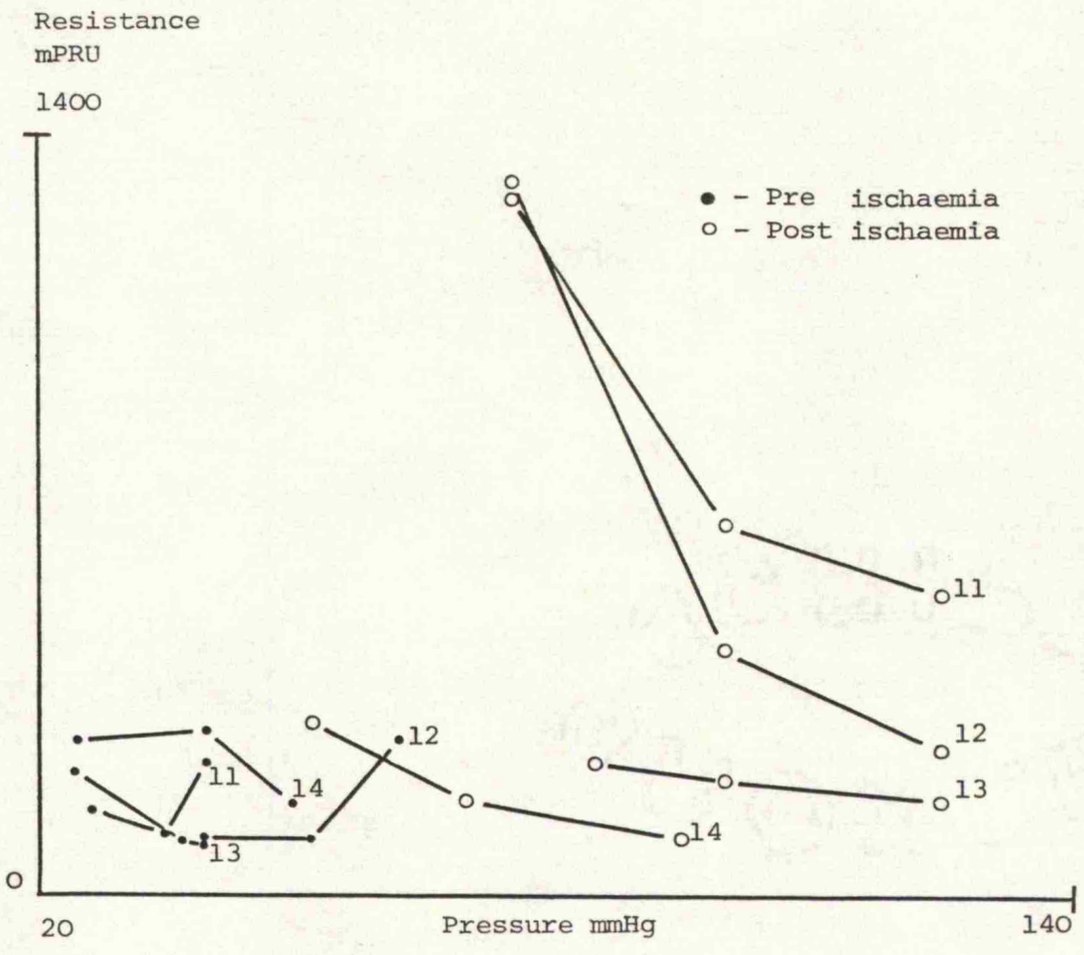
Figure 26



Manual infusion of Dextran - Upper runoff

Resistance falls with increasing flow. Ischaemia has no consistent effect on resistance.

Figure 27



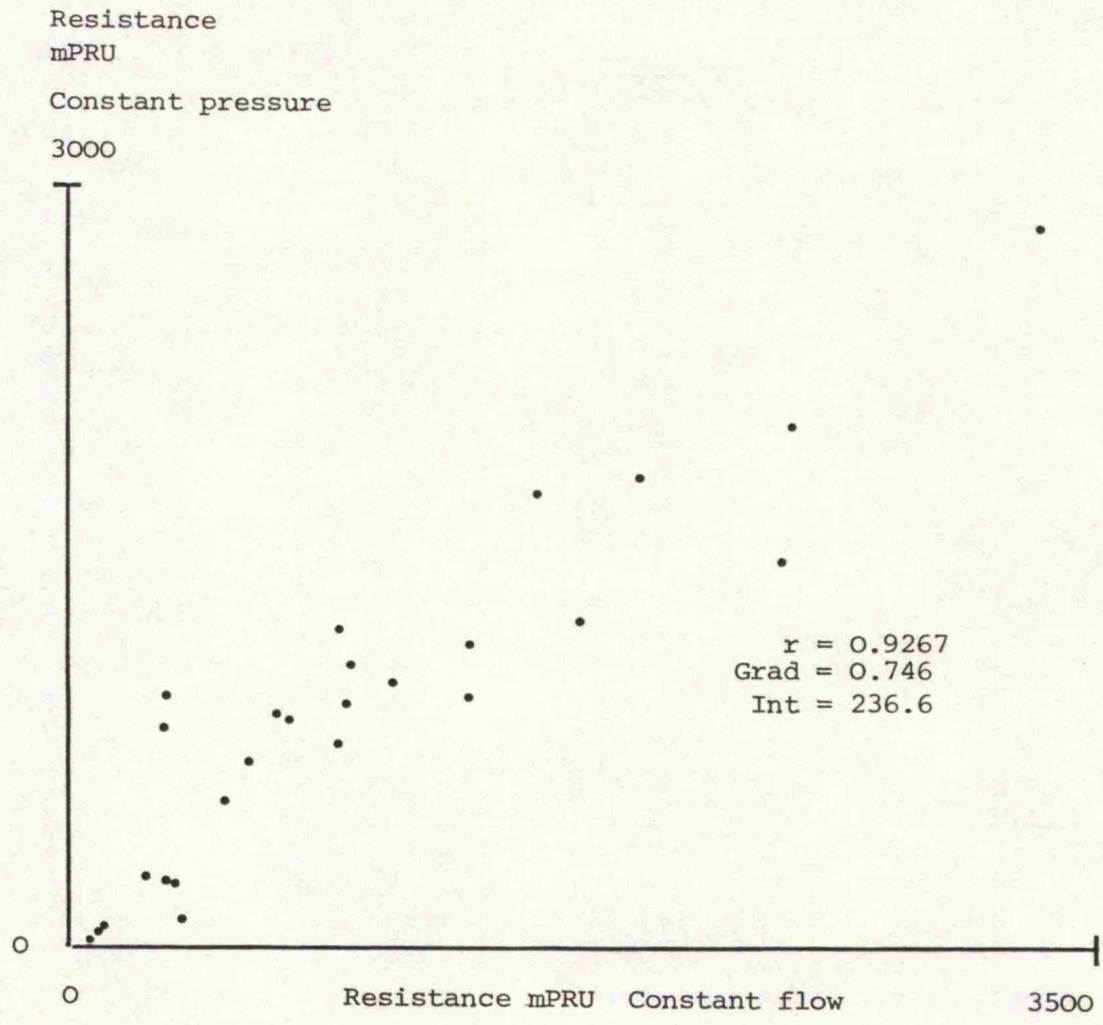
Manual infusion of Dextran - Lower runoff

There was no significant relationship between resistance and flow before or after ischaemia.

Figure 28

it was for saline. After the induction of ischaemia the resistance did not fall uniformly and in some cases rose to higher levels. This was true for both runoffs and for all three infusing solutions.

The only real comparison which could be made was between the constant pressure and constant flow data. Where flow generated by the constant pressure technique was close to the flow used in the constant flow measurements (within 10%) a comparison of resistances has been made. There were 26 suitable measurements. The correlation coefficient between them was 0.9267. The gradient of the regression line was 0.746 and the intercept 236.6. These results are shown in Table 11 in the Appendix (page C13) and in Figure 29.



Constant pressure vs. constant flow estimate of resistance. Correlation between methods is good.

Figure 29

DISCUSSION

The correlation data between the constant flow and constant pressure measurements of resistance is acceptable indicating that resistance could be measured by this technique. However in practice it was not possible, given the two runoff resistances provided by this dog model, to measure resistance at a single pressure.

SUMMARY

There were four main aims to this chapter. The first was to see whether it was possible to use a solution other than blood for infusion. This would simplify matters considerably by speeding up the preparation. Saline proved to be unsuitable because, as a result of its low viscosity, all measured resistances were low and it failed to adequately separate the two runoffs. Dextran showed some promise producing greater separation than blood presumably because of its greater viscosity. However further experiments with Dextran in humans would need to be undertaken with caution given the worrying incidence of muscle fasciculation in the dog model.

The easiest method of pressure measurement would undoubtedly be to employ a sidearm. However the resistance between the sidearm pressure transducer and the tip of the infusing cannula was so variable that it would have been necessary to recalibrate the cannula for each measurement of resistance. In addition the relationship between resistance and flow was not constant, resistance increasing with increasing flow, so that calibration for each flow rate would also be required. There were no such differences between the concentric method and the 'stab' method, and therefore

in the rest of this thesis the 'stab' method has been replaced by the concentric method.

The problem of the buckling syringes was solved easily by replacing them with more durable glass syringes.

Infusing the solution by hand at constant pressure is an attractive alternative to the use of the pump being cheaper. Where flows were similar to those achieved by the pump there was good correlation between resistances measured by the two methods. One of the problems with the experimental model was that the larger of the two runoffs was too large and that the flows generated in it were unphysiologically low. For the constant pressure method of resistance measurement this was important because there is a limit to how rapidly it is possible to inject blood or Dextran through a 100 ml syringe. Although therefore constant pressure resistance measurement did not work in this instance it might be more successful in humans where the vessels are more uniform in size.

CHAPTER 8

FEMOROTIBIAL AND FEMOROPOPLITEAL RESISTANCE

INTRODUCTION

The aim of this next chapter is to determine whether the changes applied in the second dog experiment are applicable to the human. The 'stab' method of resistance measurement has been replaced by the concentric method. Blood continues to be used as the infusion solution and, because they were done at about the same time as the second dog experiments, saline was used in a small number of cases to compare with blood. A constant flow technique is used to measure resistance.

The chapter has been divided into six sections. Each relates to resistance measured in patients undergoing either femoropopliteal or femorotibial reconstruction. The first section examines the technique of measurement. The second examines and compares resistance measured in the two groups above with the original group of amputees. The third section examines the place of papaverine induced vasodilation in measurement of resistance in the femoropopliteal group. The fourth section compares resistance measurement with radiological runoff. The fifth section relates

resistance to patency in both the femoropopliteal and femorotibial groups, and the sixth section studies the influence of site of graft insertion.

AIMS

The main aim was to apply the technique with its modifications to a further set of patients to ascertain whether resistance measurement might be useful as a predictive test in patients undergoing femorodistal reconstructive procedures.

PATIENTS

Two groups of patients undergoing reconstructive surgery have been studied in detail. The first group were all undergoing femorotibial reconstruction to a single vessel beyond the popliteal trifurcation. The details of these patients are shown in Figure 30. The mean age of the group was 68.15. There were seven females in the group. Eight had hypertension, four had had at least one myocardial infarction, and three more had angina. There were nine diabetics, one on diet control, six on oral therapy and two on insulin. All but five were either smokers or ex-smokers, and the non-smokers included two diabetics. Eight of the patients had undergone previous vascular surgery

including one who had already had an ipsilateral femoropopliteal graft. All patients had rest pain and critical ischaemia and thirteen had either ulcers or gangrene.

The operative details of the group are summarised in Figure 31. There were five femoro-posterior tibial grafts, three femoro-peroneal grafts and twelve femoro-anterior tibial grafts. All but two of the group had an adjunctive arteriovenous fistula placed at the level of graft insertion to increase flow down the leg (Ibrahim, Sussman, Dardik et al 1980). All but three of the procedures were performed with a distal anastomosis at the level of the ankle. The remaining three were performed at midcalf level. All of the operations except

FEMOROTIBIAL GRAFTS - PATIENT DETAILS

No	Age	BP^	MI	CVA	DM	Sm	XSm	PrS	Ulcer Gang	HCT	Plts
01	59	-	-	-	-	*		1	-	387	207
02	65	-	x3	-	-	*		-	*	438	199
03	84	-	-	-	-	-	-	2	*	352	413
04	67	-	x1	-	O	-	-	-	*	347	?
05	70	-	x3	-	-	*		-	-	411	221
06	67	-	-	-	O	-	-	-	*	429	343
07	79	-	-	-	-	*		-	*	427	390
08	60	*	-	-	-	*		-	-	?	?
09	68	-	-	-	I	*		3	*	393	420
10	79	*	-	-	-	-	-	-	*	360	352
11	54	*	Ang	-	-	*		4	-	413	225
12	75	*	-	-	-	-	-	-	*	364	287
13	64	*	-	-	O	*		2	*	444	750
14	71	*	-	-	O	-	-	-	*	431	313
15	74	-	Ang	-	O		*	2	*	362	351
16	63	*	-	-	I		*	-	*	369	448
17	71	-	Ang	-	O		*	-	*	320	333
18	66	-	-	-	-	-	-	-	-	411	385
19	66	*	x1	-	D		*	5	-	311	111
20	61	-	-	-	-	*		6	-	419	300

1 - Popliteal embolectomy
2 - Phenol block
3 - Lumbar sympathectomy
4 - Femoropopliteal graft
5 - Profundaplasty

? - Unknown
Ang - Angina
I - Insulin dependant
O - Oral hypoglycaemic
D - Diet control

BP^ - Hypertension
MI - Myocardial infarct
CVA - Stroke
DM - Diabetes mellitus
Sm - Smoker
XSm - Ex smoker
PrS - Previous surgery
Gang - Gangrene
* - Present
- - Absent

For further definition of labels see page 117.

Figure 30

one were performed by a single Consultant surgeon, the remaining operation being performed by the author. Six patients had a simultaneous ipsilateral amputation of toes or part of the foot. Four patients required at least one embolectomy in the immediate postoperative period. The majority of the procedures were performed with prosthetic grafts. There were nine umbilical vein grafts, five in situ saphenous vein grafts and seven composite umbilical and saphenous vein grafts. The composite vein grafts were used because of the difficulty in performing the distal anastomosis between umbilical vein and the front of an arteriovenous fistula and to reduce the cost of the procedure by reducing the length of umbilical vein required. The saphenous vein was placed distal to the umbilical vein to facilitate this anastomosis.

FEMOROTIBIAL GRAFTS - OPERATIVE DETAILS

No	Op	AVF	Graft	Level	Surg	Other operation	Emb
01	L F-PT	*	ISVG	Ankle	Con	-	*
02	R F-PT	*	UVG	Ankle	Con	-	-
03	R F-AT	*	UVG	Ankle	Con	Amp toes	-
04	R F-AT	*	UVG	Ankle	Con	Amp toes	-
05	R F-AT	*	UVG	Ankle	Con	-	-
06	L F-AT	*	UVG	Ankle	Con	-	-
07	R F-PN	*	UVG+SVG	Ankle	Con	Amp toes	*
08	L F-PN	*	UVG+BVG	Ankle	Con	-	-
09	L F-AT	*	UVG	Ankle	Con	-	-
10	R F-AT	*	UVG	Ankle	Con	Amp toes	-
11	R F-AT	*	UVG	M/C	Con	-	-
12	L F-AT	*	UVG+SVG	M/C	Con	-	-
13	R F-AT	*	UVG+SVG	Ankle	Con	Amp toes	*
14	R F-PT	*	ISVG	Ankle	Con	-	-
15	R F-PN	*	UVG+SVG	Ankle	Con	-	-
16	R F-PT	*	ISVG	Ankle	Con	-	*
17	R F-AT	*	UVG+SVG	Ankle	Con	Amp toes	-
18	R F-AT	-	UVG+SVG	Ankle	Con	-	-
19	L I-PT	*	UVG	Ankle	SReg	-	-
20	R D-AT	-	ISVG	M/C	Con	-	-

F-PT - Femoro-posterior tibial graft
F-AT - Femoro-anterior tibial graft
F-PN - Femoro-peroneal graft
I-PT - Ilio-posterior tibial graft

M/C - Mid calf

ISVG - In situ saphenous vein graft
UVG - Umbilical vein graft
UVG+SVG - Composite umbilical and saphenous vein graft
UVG+BVG - Composite umbilical and basilic vein graft

Con - Consultant surgeon
SReg - Senior registrar surgeon
* - Present
- - Absent

Figure 31

The second group were all undergoing femoropopliteal grafting. The patient details are summarised in Figure 32. Forty patients were included and they underwent a total of 44 operations. The mean age at operation was 64.04. Ten of the patients were hypertensive at the time of surgery, three had had a myocardial infarction, and two had had a previous stroke. Seven patients were diabetic, one with diet control, two on insulin and four on oral therapy. There were five non smokers, the rest being either active smokers (twenty one) or ex-smokers (fourteen). Thirteen patients had undergone previous vascular surgery. Sixteen patients had either ulcers or gangrene and the rest had either disabling claudication or rest pain.

The operative details of the group are shown in Figure 33. There were ten above knee and thirty four below knee reconstructions. Below the knee there were sixteen grafts placed on the popliteal artery above the origin of the anterior tibial artery, seven placed on the tibio-peroneal trunk, five to the tibio-peroneal trunk straddling into the posterior tibial artery, one on the tibio-peroneal trunk straddling into the peroneal artery, two to the posterior tibial artery immediately distal to its origin and three to the peroneal artery immediately distal to its origin. There were six pure umbilical vein grafts, four composite umbilical and

saphenous vein grafts, twelve polytetrafluoroethylene grafts, two reversed saphenous vein grafts, and twenty in-situ saphenous vein grafts. Fourteen of the grafts were performed by a consultant surgeon and the rest were performed by the author. There were ten additional procedures performed including six local amputations within the foot, three simultaneous aortic bifurcation grafts, and an iliac angioplasty. Eleven of the patients required an embolectomy in the immediate postoperative period. Five of the grafts were sewn to dacron from a previous aortic bifurcation graft and one graft took origin from the external iliac artery.

FEMOROPOPLITEAL GRAFTS - PATIENT DETAILS

No	Age	BP^	MI	CVA	DM	Sm	XSm	PrS	Ulcer Gang	HCT	Plts
01	73	-	-	-	-	*		4	-	?	?
02	58	-	-	-	-		*	-	-	498	251
03	73	*	-	-	-		*	-	*	424	?
04	58	-	-	-	-	*		-	-	476	316
05	60	-	-	-	-	*		-	*	401	352
06	57	-	-	-	D	*		6	*	316	471
07	79	*	-	-	-		*	-	*	410	?
08	66	-	-	-	I		*	-	*	385	269
09	72	-	-	-	O	-	-	7	*	365	315
10	80	-	-	-	-	*		-	*	471	?
11	79	-	-	-	-	*			*	557	320
12	63	-	-	-	-	*		-	-	489	273
13	69	*	-	-	-	*		-	-	441	424
14	60	-	-	-	-	*		-	-	512	273
15	54	-	x2	-	-	*		-	-	?	?
16	56	-	-	-	-	*		-	-	494	?
17	66	-	-	-	O	*		3,8	*	398	378
18	69	*	-	-	-		*	-	-	404	379
19	65	-	-	-	-	*		-	*	316	537
20	83	-	-	*	-	*		-	-	394	572
21	78	-	-	-	-	-	-	-	-	429	285

Figure 32 (1)

Cont...

FEMOROPOPLITEAL GRAFTS - PATIENT DETAILS (Cont)

No	Age	BP^	MI	CVA	DM	Sm	XSm	PrS	Ulcer Gang	HCT	Plts
22a	62	-	-	-	-	*		-	*	413	256
22b	63	-	-	-	-	*		4	*	400	265
23	58	-	-	-	-	*		6	-	482	184
24	59	-	-	-	-		*	-	-	388	294
25	75	-	-	-	-	*		-	*	413	278
26	65	-	x1	-	I		*	-	*	424	528
27	42	-	-	-	-	*		-	-	449	346
28	70	-	-	-	-	-	-	-	*	497	346
29	21	-	-	-	-	-	-	-	-	485	?
30	82	*	-	-	-	*		2	*	268	198
31a	55	*	-	-	-	*		6	-	359	?
31b	55	*	-	-	-		*	6,9	-	362	314
32	42	-	-	-	-	*		-	-	499	360
33a	67	-	-	-	-		*	-	-	375	385
33b	68	*	-	-	-		*	9	-	?	?
34	72	*	-	-	-		*	-	-	388	350
35	60	-	-	-	-		*	-	-	462	310
36	60	-	-	-	-		*	5	-	474	?
37	58	-	-	-	-		*	-	-	388	234
38a	74	*	*	*	O	*		5,2	*	397	211
38b	75	*	*	*	O	*		2,5,9	*	397	401
39	57	-	-	-	-	*		-	-	469	314
40	60	*	-	-	O	-	-	-	*	421	502

6 - Aortic bifurcation graft
7 - Amputation of toes
8 - Carotid endarterectomy
9 - Contralateral femoropopliteal graft

For a detailed definition of labels see page 111

Figure 32 (2)

FEMOROPOPLITEAL GRAFTS - OPERATIVE DETAILS

No	Operation	Graft	Level	Surg	Other operation	Embol
01	L F-PT	UVG	B/K	SR	-	-
02	R F-TPT/PT	UVG	B/K	Con	-	-
03	L F-POP	ISVG	B/K	SR	Amp toes	-
04	R F-POP	UVG	A/K	SR	-	-
05	L F-POP	PTFE	B/K	Con	-	-
06	R D-POP	UVG	B/K	Con	ABG	*
07	L F-POP	ISVG	B/K	SR	-	-
08	L F-POP	UVG+SVG	B/K	Con	Amp toes	-
09	L F-POP	PTFE	B/K	Con	-	*
10	R F-POP	ISVG	B/K	Con	-	*
11	L F-TPT/PT	ISVG	B/K	SR	-	*
12	R F-TPT/PT	ISVG	B/K	Con	ABG	-
13	L F-TPT	ISVG	B/K	SR	-	-
14	L D-POP	UVG+SVG	B/K	Con	ABG	-
15	L F-TPT/PN	UVG+SVG	B/K	Con	-	-
16	R F-POP	ISVG	A/K	SR	-	-
17	R F-TPT/PT	ISVG	B/K	SR	Amp toes	-
18	L F-POP	PTFE	B/K	SR	-	*
19	R I-POP	PTFE	B/K	?	-	-
20	L F-POP	PTFE	B/K	SR	-	-
21	L F-TPT	PTFE	B/K	SR	-	-

Figure 33 (1)

Cont...

FEMOROPOPLITEAL GRAFTS - OPERATIVE DETAILS (Cont)

No	Operation	Graft	Level	Surg	Other operation	Embol
22a	R F-POP	RSVG	A/K	SR	-	*
22b	R F-TPT	PTFE	B/K	Con	-	-
23	L F-POP	PTFE	A/K	SR	-	-
24	L F-POP	ISVG	B/K	SR	-	-
25	L F-POP	PTFE	A/K	SR	Iliac ang	-
26	L F-POP	RSVG	A/K	SR	Amp foot	-
27	R F-POP	PTFE	A/K	SR	-	-
28	L F-TPT	ISVG	B/K	SR	-	*
29	R F-POP	ISVG	B/K	SR	-	*
30	L F-PN	ISVG	B/K	Con	-	*
31a	R D-POP	UVG	B/K	SR	-	-
31b	L D-TPT	ISVG	B/K	SR	-	*
32	R F-POP	PTFE	A/K	SR	-	-
33a	L D-POP	PTFE	A/K	Con	-	-
33b	R F-POP	ISVG	A/K	SR	-	-
34	L F-TPT	UVG+SVG	B/K	SR	-	-
35	L F-PT	ISVG	B/K	Con	-	*
36	L F-TPT	UVG	B/K	SR	-	-
37	L F-POP	ISVG	B/K	SR	-	-
38a	L F-PN	ISVG	B/K	Con	AMP TOES	-
38b	R F-PN	ISVG	B/K	SR	-	-
39	R F-TPT/PT	ISVG	B/K	SR	-	-
40	R F-POP	ISVG	B/K	SR	AMP TOES	-

F-PT - Femoro-posterior tibial graft
F-AT - Femoro-anterior tibial graft
F-PN - Femoro-peroneal graft
I-PT - Ilio-posterior tibial graft
D-TPT - Dacron-tibioperoneal trunk
M/C - Mid calf

ISVG - In situ saphenous vein graft
UVG - Umbilical vein graft
UVG+SVG - Composite umbilical and saphenous vein graft
RSVG - Reversed saphenous vein graft
Iliac Ang - Iliac angioplasty
ABG - Aortic bifurcation graft
Amp - Amputation

Con - Consultant surgeon
SR - Senior registrar surgeon
B/K - Below knee graft insertion
A/K - Above knee graft insertion

Figure 33 (2)

METHODS

In each case the artery to be reconstructed was first mobilised and controlled with silicone rubber slings. In every case an arteriogram was performed using the largest cannula compatible with the size of the vessel under study. This was done to confirm or expand upon the findings of the preoperative arteriogram. An inflow study was performed with measurement of femoral/aortic pressure gradient before and after papaverine injection (Sako 1966 and Quin, Evans and Bell 1975). If this investigation indicated the presence of proximal disease proximal reconstruction was performed prior to distal reconstruction. Next 100ml of blood was withdrawn from the common femoral artery into two previously heparinised glass syringes and these were mounted onto the Harvard pump. For the femorotibial grafts the artery under study was then cannulated with a size 20 Cathlon cannula. For the femoropopliteal grafts the popliteal artery was cannulated with the composite double lumen cannula previously described.

Chronologically most of the femorotibial grafts were performed before most of the femoropopliteal grafts. In the early stages a smaller Harvard pump was in use and the flows generated were slightly different from those measured latterly. For most of the

femorotibial and for several of the early femoropopliteal grafts resistance was measured at 9.5, 19.1, 38.2, 76.4, and 190 ml/min. When the new pump became available resistance was measured at 45, 81, 117, and 153 ml/min. From patient 37 onwards pressure was only measured at 81 ml/min. The low rates of infusion in the early experiments were abandoned because the pressure generated by the low infusion rate was often insufficient to raise the pressure above the prevailing collateral pressure. This would clearly render any resistance measurement meaningless. In the femoropopliteal group resistance was measured both before and after the administration of papaverine. This was not done in the femorotibial group and reflects the fact that most of the grafts were performed before the femoropopliteal grafts. Venous pressure was measured in every case in the femoral vein by a separate needle cannulation.

In a small group of femoropopliteal grafts pressure was measured simultaneously by the concentric cannula and by the sidearm technique to confirm the findings noted in the animal experiments.

After grafting, pressure and flow in the graft itself were recorded both before and after the administration of papaverine so that the resulting resistance could be compared with the resistance

measured prior to grafting.

FOLLOW UP

After the operation all patients in the femoropopliteal group and the majority of the patients in the femorotibial group were followed up either until the graft occluded or until the February 1st 1986. The minimum follow up time was eight months though all but two grafts had been performed more than 13 months previously. Three of the femorotibial group had been referred from distant centres and were followed up by the referring Surgeon locally. Details of outcome were obtained by telephone enquiry. Where there was any doubt about continuing patency a combination of ankle pressure measurement and Duplex scanning was used to resolve the question.

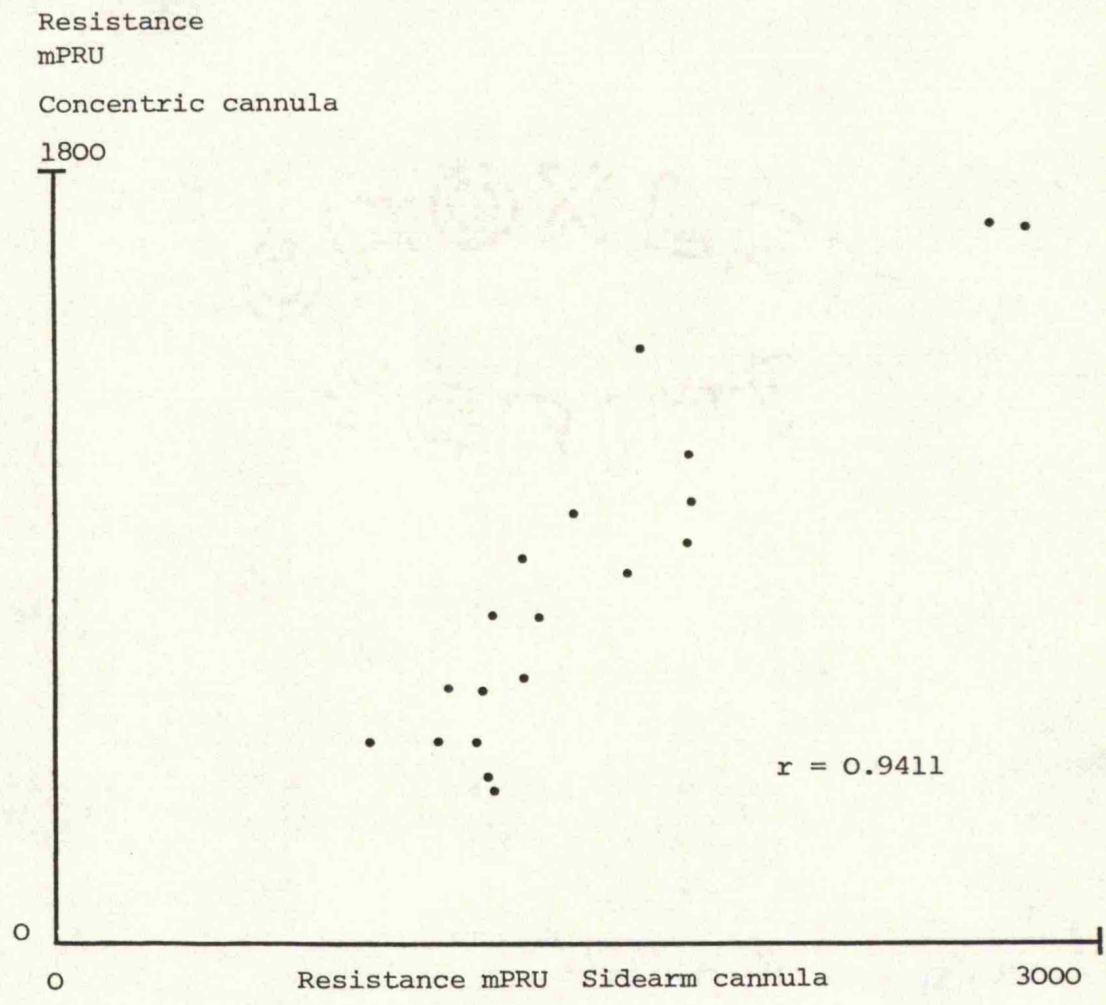
RESULTS

The results of these experiments will be presented and discussed under a number of headings. At the end of the Chapter the results will be summarised.

METHOD OF PRESSURE MEASUREMENT

In ten patients undergoing femoropopliteal grafting sidearm and concentric cannula measurements of pressure have been made both before and after papaverine. These measurements of pressure have been made with both blood and saline. The results of this experiment are shown in Tables 1-3 in the Appendix (pages D3-5). Resistance has been calculated by both of the methods and the ratio of concentric resistance to sidearm resistance has been calculated.

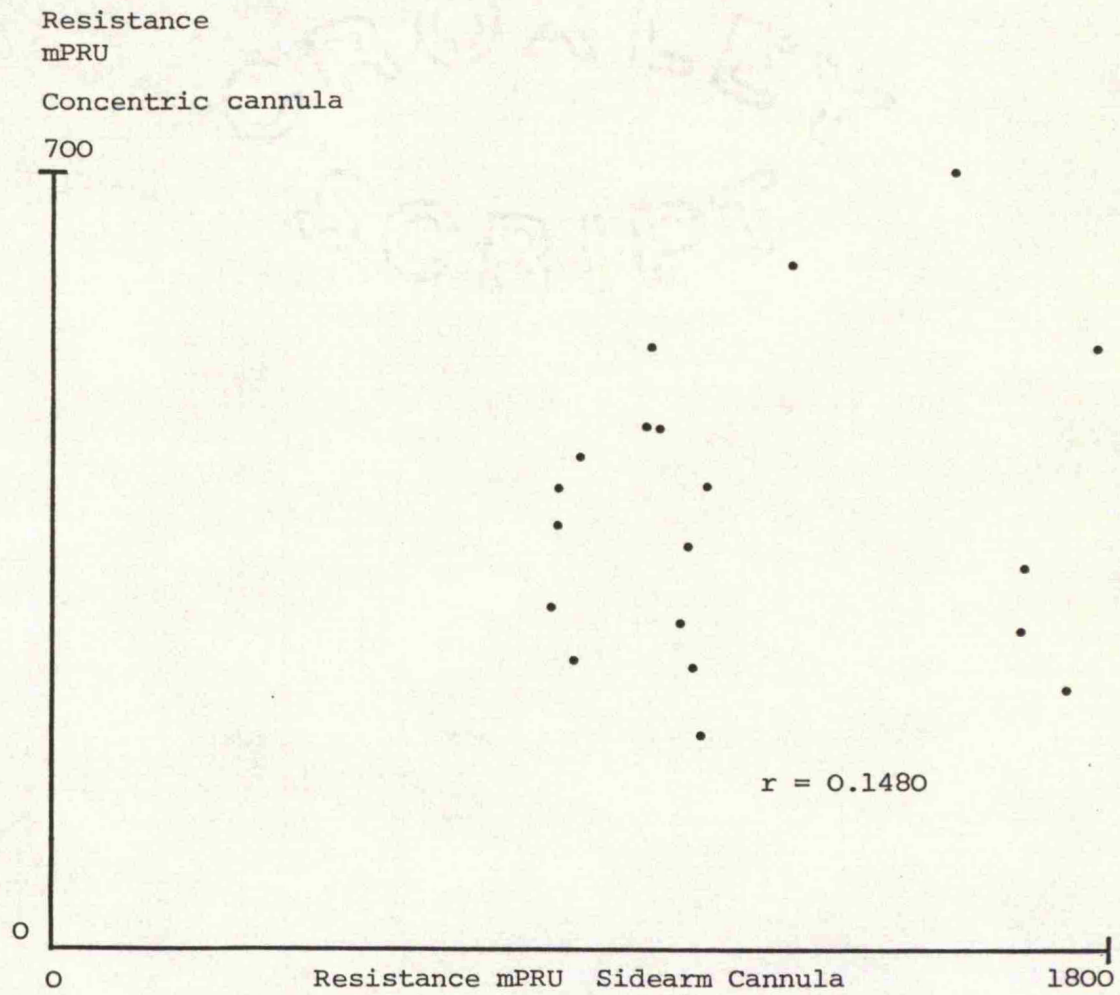
1. **Blood.** The results show that in each case the concentric resistance is lower than the sidearm resistance. The ratio between the two methods however varies widely between 0.28 and 0.815. The same findings are true after papaverine where the ratio is between 0.13 and 0.52. Prior to papaverine there is an acceptable correlation between the two methods r=0.9411 (Figure 34). Interestingly however the same correlation after papaverine is very poor r=0.1480



Concentric vs. Sidearm resistance measurement

Correlation between the sidearm and concentric measurements of resistance before papaverine is good.

Figure 34



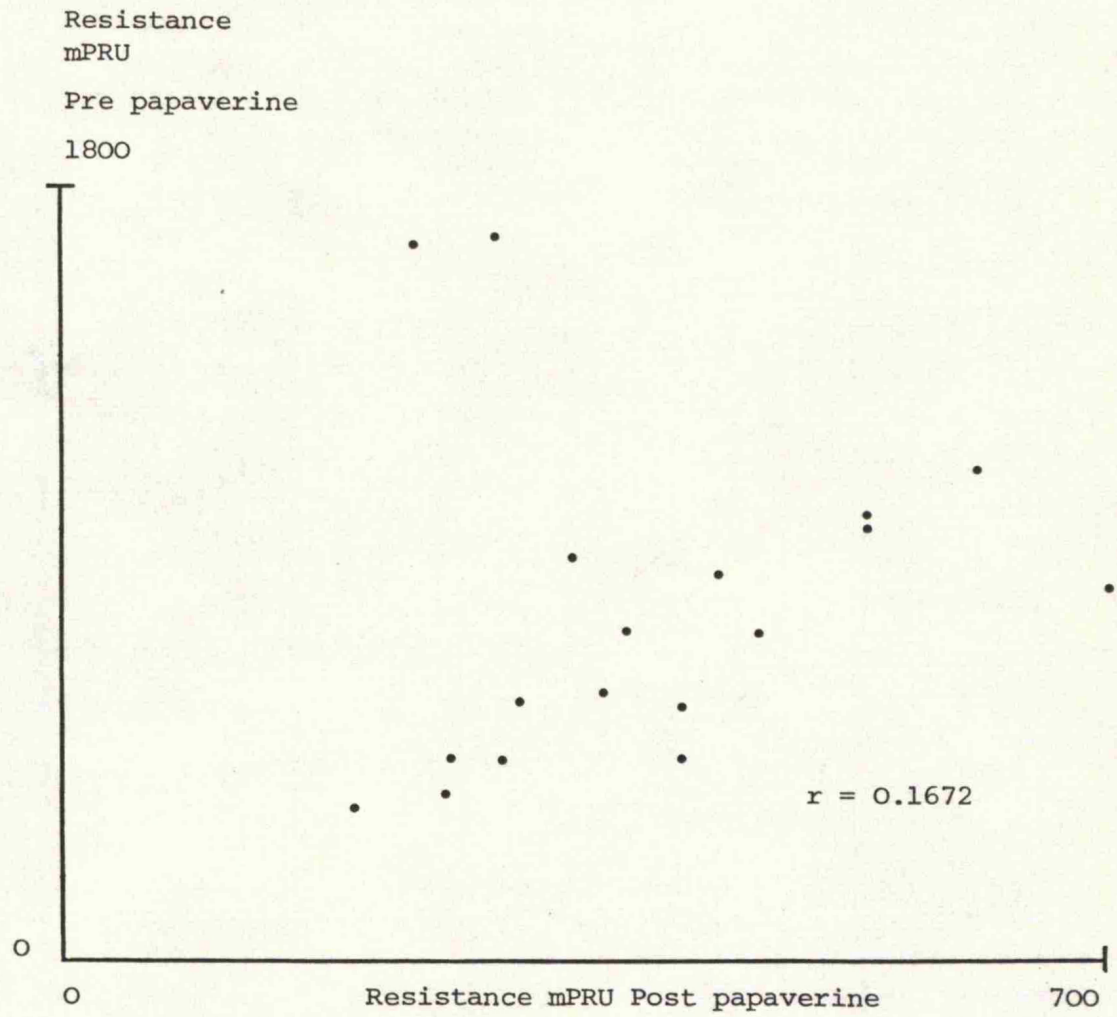
Concentric vs. Sidearm resistance measurement

Correlation between the sidearm and concentric measurements of resistance after papaverine is poor.

Figure 35

(Figure 35). Similarly the correlation between resistances measured before and after papaverine but by the same method is poor (for the concentric cannula r=0.1672 (Figure 36) and for the sidearm r=0.8348 (Figure 37). The mean difference in resistance between the two methods before papaverine was 714 mPRu (SE 46). After papaverine the mean difference was 819 mPRU (SE 79).

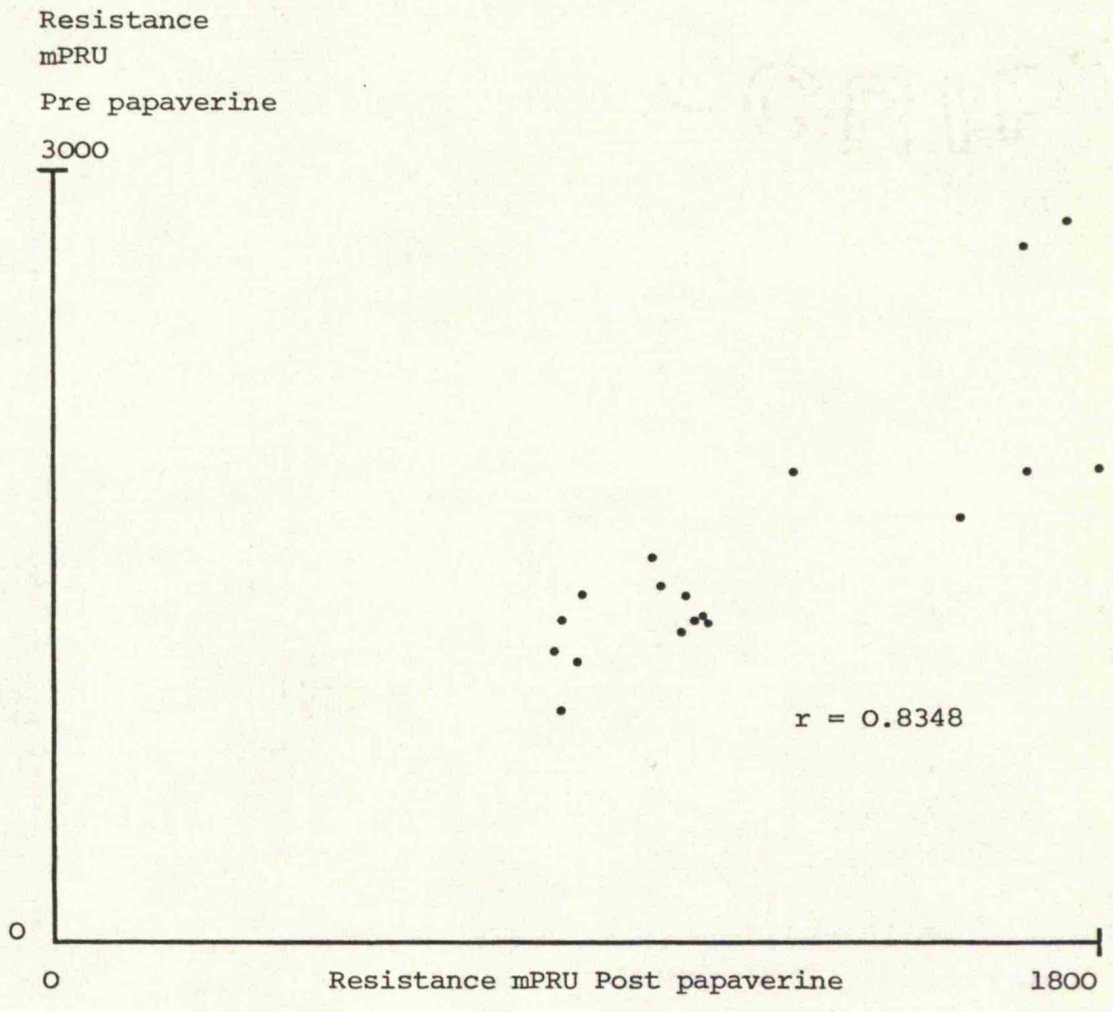
2. **Saline.** For saline there were only measurements available for six patients (Table 3 in the Appendix on page D5). As with the blood, the resistance measured by the concentric cannula was lower than that measured by the sidearm method. The ratio of the two resistances on any one occasion was as wide as it was for the blood measurements 0.28-0.84. The correlation between the two methods was poor prior to papaverine r=0.7086, and there were no results in the saline group after papaverine. The resistance measured with blood was higher than that measured with saline and the correlation between the resistances measured with the two different fluids was poor r=0.5690 for the concentric cannula and r=0.8829 for the sidearm. The mean difference in resistance measured by the two methods where comparison between fluids was available was 633mPRU (SE 66) for blood and 380 mPRU (SE 78) for saline.



Resistance pre and post papaverine - concentric cannula

There is poor correlation between resistances measured before and after papaverine by the same method.

Figure 36



Resistance pre and post papaverine - sidearm cannula

There is poor correlation between resistances measured before and after papaverine by the sidearm cannula.

Figure 37

DISCUSSION

If the two methods of pressure measurement were interchangeable the ratio or resistances measured should have been the same. In this small series there was wide variation. This is probably due to variations in the size of the component parts of the concentric cannula. Small variations in the length and diameter of either the cannula or the epidural catheter threaded through it or in the internal dimensions of the three way tap allowing attachment of the sidearm will effect the resistance measured in the sidearm. The results with saline indicate no advantage in its use since the variation between methods is as wide as for blood. It is interesting to note that the mean difference in resistance between methods with saline is approximately half that found with blood. This is a clear manifestation of the effect of the higher viscosity of blood compared with saline resulting in a proportionately higher sidearm pressure recording with blood than with saline. The difference is significant (t-test $p<0.02$).

Section 2

RESISTANCE AND OPERATION - PRE-PAPAVERINE

INTRODUCTION

With the addition of the femorotibial and femoropopliteal groups to the amputation group of patients there are three distinct groups of patients available for study. In this section the resistance measured for the three groups is compared. There has been no attempt to divide the patients into subgroups and the comparison has been made at all the available flow rates. Eight patients have been excluded. In the femorotibial group patients 11, 12, and 20 have been left out because resistance was not measured at ankle level as it was for the rest and it was felt that this would bias the results. In the amputation group patients 5, 6, and 11 have been excluded because resistance was measured in the above knee popliteal artery. In the femoropopliteal group patients 6 and 14 were excluded because the results were technically unsatisfactory at the time of measurement. In both there was significant leakage of blood around the cannula during the infusion resulting in a lower result than would have been expected.

AMPUTATION

The results for this group have already been described in Chapter 6. The main results are shown again in Figure 38. In this group resistance has been measured at five flow rates; 9.5, 19.1, 38.2, 76.4, and 190 ml/min. The significant differences between the resistances measured at the five flow rates is also summarised in Figure 38.

FEMOROTIBIAL GROUP

The results for this group are shown in Table 4 in the Appendix (pages D6-8). It will be noted that in this group the flows at which resistance has been measured change approximately half way through the series. This coincided with the acquisition of a new Harvard pump which had slightly different flow ranges from the old one. The new range of flows was 45, 81, 117, and 153 ml/min. The results from Table 4 in the Appendix have been summarised by flow rate in Figure 39. In the following results levels of significance refer to resistances measured at higher flow rates for each individual flow. Resistance at 9.5 ml/min was significantly higher than that

AMPUTATION SUMMARY

Name	9.5	19.1	38.2	76.4	190 ml/min
01	3265	2200	1465	1050	689
02	20680	16565			
03	18020	17740			
04	11450	10180			
		35640			
05	12630	11100	3430	4830	
06	3350	2140	1410	1050	780
07	9530	6940	4030	2070	1200
08	526	1780	1570	916	368
09	14750	9630	6280	5185	
10	9685	5235	2830	1600	
11			314	222	110
12	4000		2565	1910	1410
Mean	11960	8351	2654	2092	759
SE	2927	1922	628	617	218

^--- p<0.001 ---^

^----- p<0.01 -----^

^---- p<0.01 ----^

^- p<0.05 -^

Figure 38

measured at 45 ml/min $p<0.001$, 81 ml/min $p<0.001$, 117 ml/min $p<0.001$, and 153 ml/min $p<0.001$. Resistance at 9.5 ml/min was lower than that measured at 19.1 ml/min. Resistance at 19.1 ml/min was significantly higher than resistance measured at all the other flow rates except 38 ml/min; at 45 ml/min, 81 ml/min, 117 ml/min and 153 ml/min $p<0.001$; at 76 ml/min $p<0.01$. Resistance at 38.2 ml/min was significantly greater than resistance at 45 ml/min, 81 ml/min, 117 ml/min and 153 ml/min $p<0.001$. At 45 ml/min resistance was significantly less than that measured at 76 ml/min $p<0.001$ and 117 ml/min $p=0.009$. At the other flow rates there were no significant differences. At 76 ml/min resistance was significantly greater than at 81 ml/min, and at 117 ml/min $p<0.001$; it was also greater than at 153 ml/min $p<0.01$. At 81 ml/min there were no differences with higher flow rates. Similarly there was no difference between resistances at 117 ml/min and 153 ml/min. These results are summarised in Figure 40. It will be noted that in Figure 41 the resistances at 38.2 ml/min have been combined with those at 45 ml/min as have the resistances at 76.4 ml/min and 81 ml/min. This has been done since the resistances have been measured at similar flow rates. However in the femorotibial group there are significant differences between the resistances measured individually and those that have been grouped together;

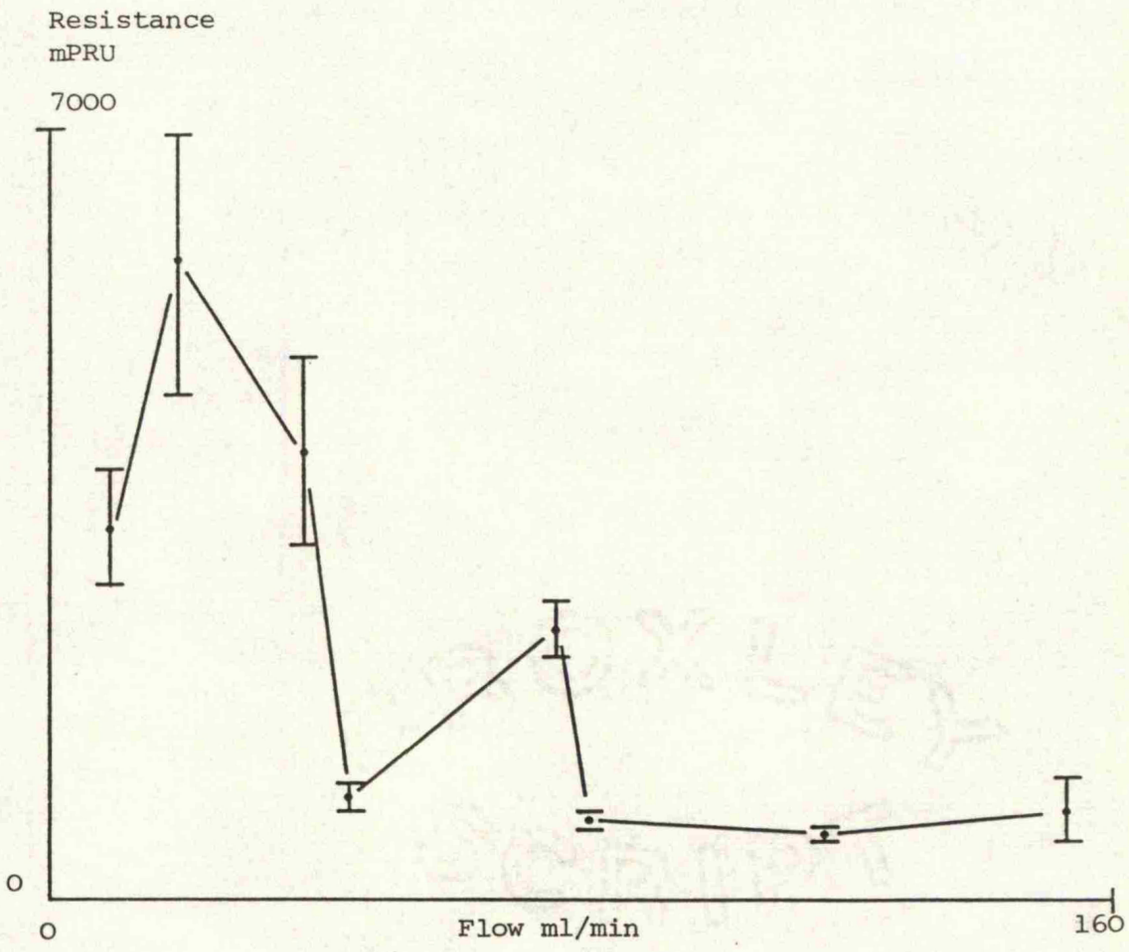
FEMOROTIBIAL GROUP - SUMMARY OF RESISTANCE

PRE PAPAVERINE Flow	9.5	19.1	38.2	45	38/45 ml/min
	1894	5555	3120	911	911
	5778	2250	3760	777	3120
	3263	3507	1727	1111	3760
	3263	3455	2905	1377	1727
	4105	9267	2853	888	2905
	5368	4607	5628		2853
	1684	4397	3455		5628
	2526	12251	2329		3455
	2842	6806	10314		2329
			4973		10314
					4973
					777
					1111
					1377
					888
Mean	3413	5788	4106	1012	3075
SE	505	1127	823	118	666

Flow	76	81	76/81	117	153 ml/min
	1990	641	641	461	352
	2380	790	1990	726	2183
	1650	1012	2380	623	738
	2610	691	1650	871	790
	2486	950	2610	858	732
	3599		2486	641	614
	3036		3599		
	1518		3036		
	3376		1518		
			3376		
			790		
			1012		
			691		
			950		
Mean	2516	816	1983	696	901
SE	257	80	295	69	289

Figure 39

Resistance at 38/45 ml/min is significantly higher than at 45 ml/min alone $p<0.001$ but not significantly different from that measured at 38.2 ml/min. Similarly resistance at 76/81 ml/min is significantly greater than resistance at 81 ml/min alone $p<0.025$ but not significantly different from the resistance at 76.4 ml/min.

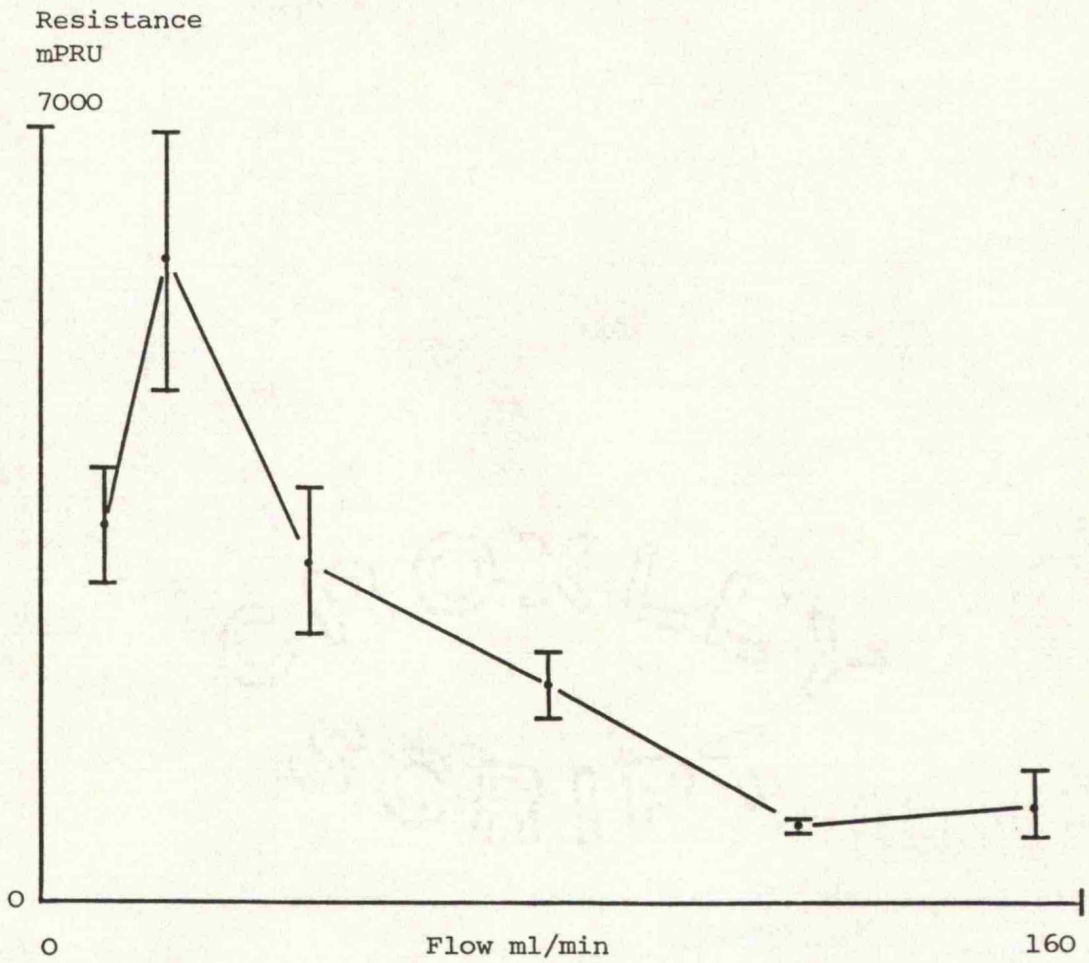


Femorotibial grafts - Resistance ± SE vs. flow

Resistance falls with increasing flow.

Resistance at 45 and 81 ml/min is significantly lower than at 38 and 45 ml/min.

Figure 40



Femorotibial grafts - Mean resistance ± SE vs. flow

38/45 ml/min and 76/81 ml/min combined. After an initial rise resistance falls significantly with increasing flow.

Figure 41

DISCUSSION

As with the amputation group the resistance measured in the femorotibial group falls with increasing flow rates. The measurements are complicated by the change in flow rates that occurred half way through this group. The new flow rates were chosen partly through necessity having acquired the new pump and partly because it had become clear that resistance measured at the very low flow rates was both excessively high and unreliable. 45 ml/min was as close as it was possible to get to 38 ml/min and 81 ml/min was as close as it was possible to get to 76 ml/min. The extra flow rate at 117 ml/min was chosen to fill the gap between 81 ml/min and 153 ml/min. The differences in resistance between 38 and 45 ml/min and between 76 and 81 ml/min are significant but in spite of this the two groups of flows have been grouped together.

FEMOROPOPLITEAL GROUP

The results for the femoropopliteal group are shown in Table 5 in the Appendix (pages D9-13) and are summarised in Figure 42. As with the femorotibial group some of the patients have had resistance measured at the earlier set of flows. The majority however have been measured with the new pump. Patients 37, 38, 39, and 40 have had resistance measured only at a single flow rate - 81 ml/min. The resistance fell with increasing flow rates, and the mean resistances are plotted on Figure 43. The resistance measured at 9.5 ml/min was significantly greater than that measured at any other flow rate; 38 ml/min $p=0.0084$, 45 ml/min $p=0.0016$, 76 ml/min $p=0.0001$, 81 ml/min $p=0.00003$, 117 ml/min $p=0.00003$, 153 ml/min $p=0.00003$. At 38.2 ml/min resistance was again higher than at higher flow rates; 76 ml/min N/S, 81 ml/min $p=0.008$, 117 ml/min $p=0.0003$, and 153 ml/min $p=0.00007$. At 45 ml/min resistance was higher than at 76 ml/min $p<0.05$, 81 ml/min $p=0.001$, 117 ml/min $p<0.00003$, and 153 ml/min $p<0.00003$. Resistance at 76 ml/min was higher than resistance at 153 ml/min $p=0.0089$, at 117 ml/min there was no significant difference $p=0.0823$. Resistance at 81 ml/min was significantly higher than at 117 ml/min $p=0.0139$, and at 153 ml/min $p=0.0005$. Resistance at 117 ml/min was not

FEMOROPOPLITEAL GROUP - SUMMARY OF RESISTANCE

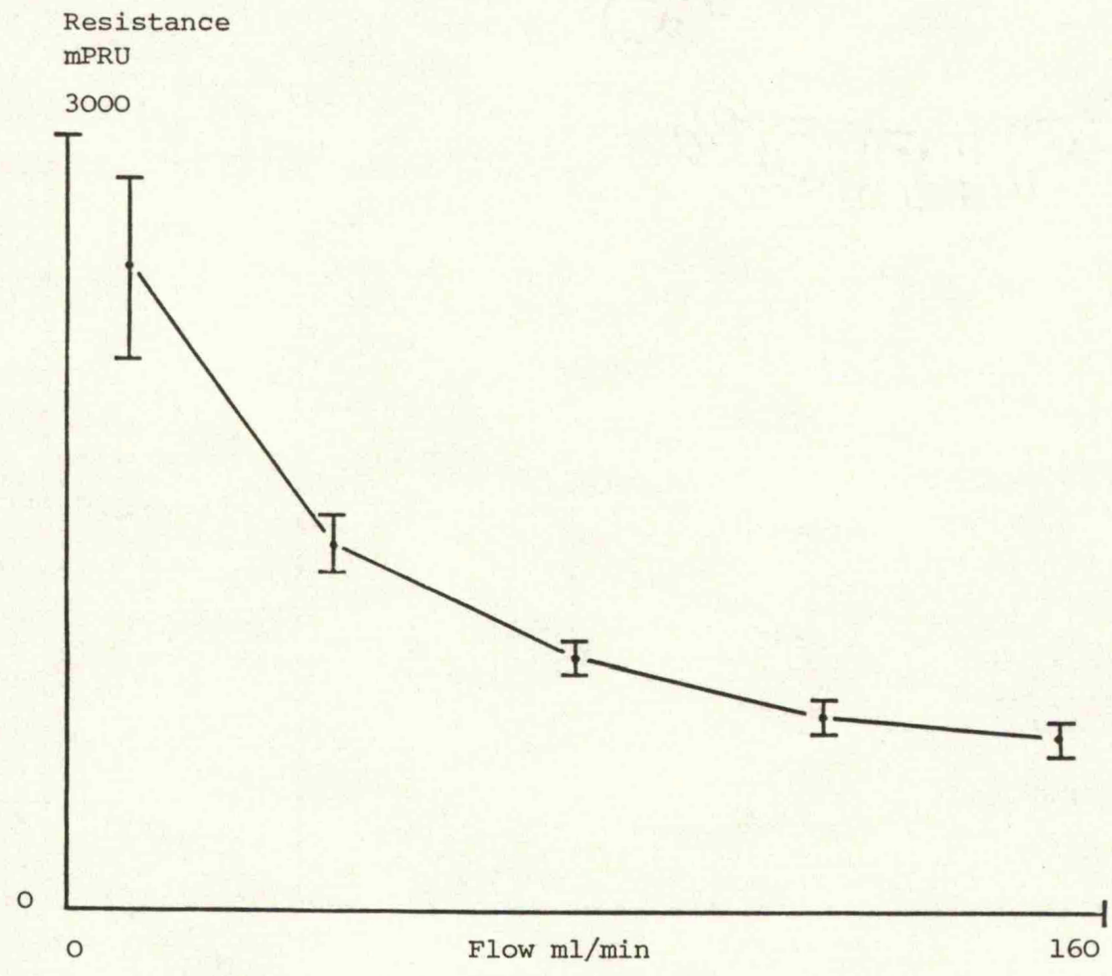
PRE PAPAVERINE Flow	9.5	38.2	45	38/45	76 ml/min
	3360	1250	977	1250	1210
	1315	921	1040	921	552
	3100	2020	1350	2020	1380
	2080	1140	1777	1140	888
	1460	916	711	916	511
	1150	759	1522	759	615
	3340	968	1244	968	667
	3910	2610	1577	2610	2240
	4105	2380	800	2380	1500
	2050	3130	711	3130	1575
	1510	1130	1022	977	618
			866	1040	
			733	1350	
			1688	1777	
			1155	711	
			1822	1522	
			2844	1244	
			2044	1577	
			1911	800	
			1200	1130	
			1600	711	
			1200	1022	
			1600	711	
			1200	1022	
			1377	866	
			2688	733	
			755	1588	
			1355	1155	
				1822	
				2844	
				2044	
				1911	
				1200	
				1600	
				1200	
				1377	
				2688	
				755	
				1355	
Mean	2489	1565	1383	1434	1068
SE	346	258	113	107	176

Figure 42 (1)

FEMOROPOPLITEAL GROUP - SUMMARY OF RESISTANCE

PRE PAPAVERINE Flow	81	76/81	117	153 ml/min
	740	1210	641	843
	666	552	520	530
	1086	1380	760	289
	469	888	367	592
	981	511	730	486
	913	615	663	1780
	1148	667	931	987
	580	2240	461	549
	567	1500	452	660
	728	1575	512	300
	641	740	495	558
	493	666	358	712
	1209	1086	957	379
	950	469	743	392
	1259	981	1025	405
	2123	913	1641	385
	1432	1148	1145	294
	1296	580	893	810
	901	618	649	549
	913	567	752	895
	987	728	598	1568
	765	641	760	967
	1000	493	1598	777
	1913	1209	393	483
	469	950	982	614
	962	1259		470
	1074	2123		620
	802	1432		1274
	1037	1296		359
	592	901		
		913		
		987		
		765		
		1000		
		1913		
		469		
		962		
		1074		
		802		
		1037		
		592		
Mean	956	986	761	673
SE	71	68	68	68

Figure 42 (2)



Femoropopliteal grafts - Mean resistance ± SE vs. flow

Resistance falls progressively with increasing flow. There are significant differences in resistances measured between adjacent flows.

Figure 43

significantly different from resistance at 153 ml/min. When the results at 38 ml/min and 45 ml/min were combined there was no significant difference between the combined resistance and resistance measured at either flow singly. Similarly combined resistance at 76 ml/min and 81 ml/min was not significantly different to that measured at either of the flow rates singly.

DISCUSSION

The same decrease in resistance has been shown with increasing flow for this group as the two preceding groups. In this group the change in flow rates has had less effect on the results, since there is no significant difference between the combined and single resistance measurements. It is therefore reasonable to perform further comparisons using the combined figures. Resistance has been shown to fall with increasing flow in a remarkably consistent way in dogs, and in patients undergoing amputation, femorotibial and femoropopliteal grafting. In each situation the resistance falls rapidly at low flow rates and tends to level out from 80 ml/min. For this reason, and to simplify and speed up the procedure in theatre, resistance has only been measured at 81 ml/min latterly in the femoropopliteal group. It is probable that a flow of >100 ml/min would be more desirable but since the majority of the early studies have been performed most frequently at 76, 81, or 83 ml/min this rate was chosen.

INTERGROUP COMPARISON

Using the raw data obtained from the three groups it is possible to draw comparisons between them.

(1) **9.5 ml/min.** The resistance of the amputation group was greater than the femorotibial group which was in turn greater than the femoropopliteal group; $p<0.01$ and p= NS respectively.

(2) **19.1 ml/min.** There was only data available for the amputation and femorotibial groups. Whilst the resistance of the femorotibial group was lower than the resistance of the amputation group; mean 5788 mPRU SE 1127 vs. mean 8862 mPRU SE 2276 the difference was not significant.

(3) **38.2 ml/min.** The resistance of the femorotibial group was actually higher than that of the amputation group but the difference was not significant; mean 4106 mPRU SE 823 vs. mean 3123 mPRU SE 808. Both the femorotibial and amputation groups had significantly higher resistance than the femoropopliteal group; $p<0.001$ and $p<0.025$ respectively (mean resistance of femoropopliteal group 1565 mPRU SE 258).

(4) **45 ml/min.** There was no data for the amputation group but the resistance of the femorotibial group (mean 812 SE 227) was significantly lower than the femoropopliteal group (mean 1383 mPRu SE 113);

P=0.03.

(5) **Combined 38.2 and 45 ml/min.** The combined group resistances were only available for the femorotibial and femoropopliteal groups where the resistance of the former (Mean 3075 mPRU SE 666) was significantly higher than the latter (Mean 1434 mPRU SE 107); p<0.005.

(6) **76.4 ml/min.** The femorotibial resistance was higher than the amputation group and again there was no significant difference (mean 2516 mPRu SE 257 vs. mean 2121 mPRU SE 701). Both of these groups had significantly higher resistance than the femoropopliteal group (Mean 1068 mPRU SE 176); P<0.001 and P=0.025 respectively.

(7) **81 ml/min.** At this flow measurements were available for the two reconstruction groups. Resistance of the femorotibial group (Mean 816 SE 80) was slightly but not significantly lower than the femoropopliteal group (Mean 956 mPRU SE 71)

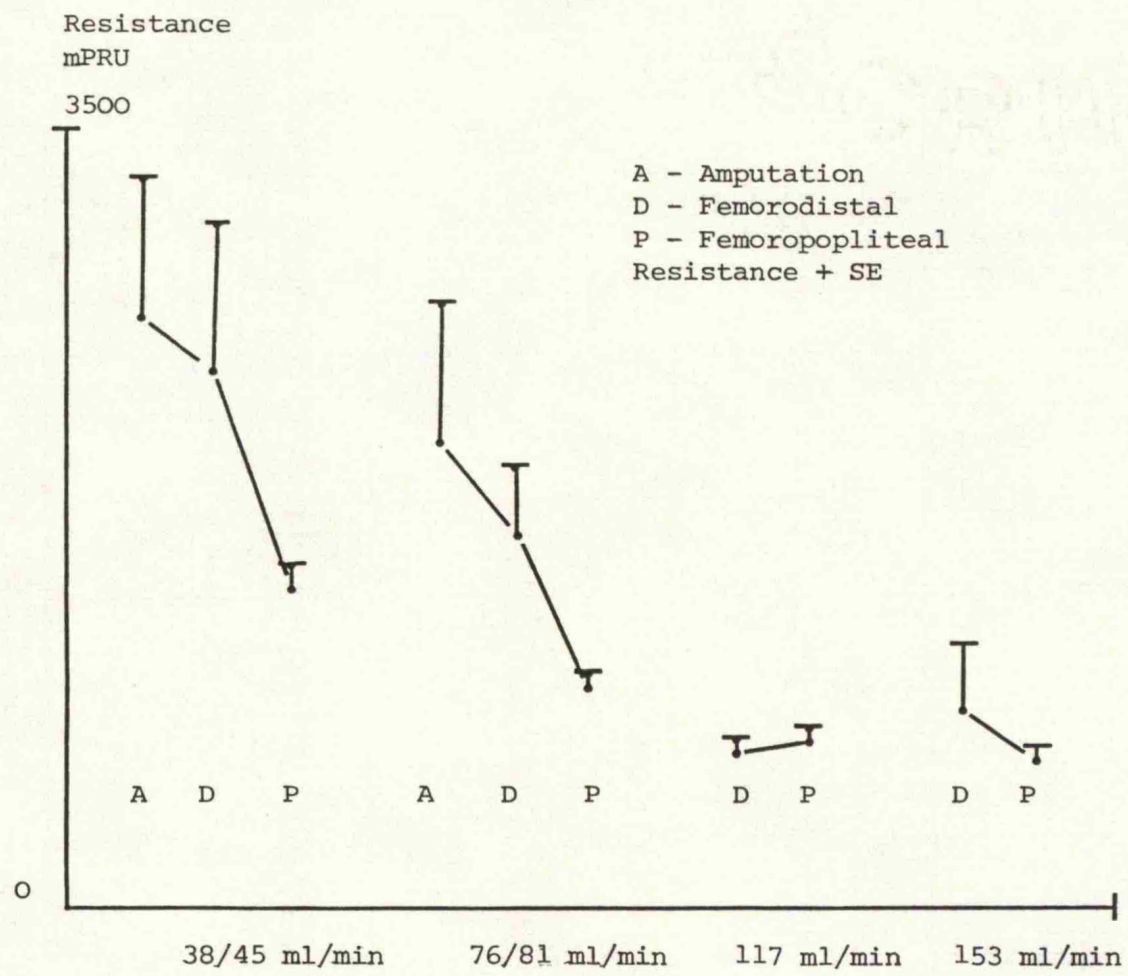
(8) **Combined 76.4 and 81 ml/min.** For the combined groups the femorotibial (Mean 1983 mPRU SE 295) resistance was significantly higher than the femoropopliteal resistance (Mean 986 mPRU SE 68); P<0.0003.

(9) **117 ml/min.** Measurements at this flow rate were not available for the amputation group. The

resistance of the femoropopliteal group (Mean 761 mPRU SE 68) was slightly higher than the resistance of the femorotibial group (Mean 696 mPRU SE 69) but the differences were not significant.

(10) **153 ml/min.** Again at this flow figures were only available for the femoropopliteal and femorotibial groups. Femoropopliteal resistance (Mean 673 SE 68) was lower than femorotibial resistance (Mean 901 SE 289) but the differences were not significant.

The results at 38/45 ml/min, 76/81 ml/min, 117 ml/min, and 153 ml/min are shown in graph form in Figure 44.



Resistance vs. flow - pre papaverine - Three groups

At 38/45 and 76/81 ml/min femoropopliteal resistance is significantly lower than in either of the other groups.

Figure 44

DISCUSSION

Comparing the three groups it is clear that the resistances measured at the extremes of flow are not able to separate the three groups. At 9.5, 19.1, 117, and 153 ml/min there were no significant differences. The reason for this is not clear. At low flow rates the pressure generated by the infusion is often not significantly higher than the preceding collateral pressure (Tables 4 and 5 in the Appendix (pages D6-13). Ideally infusion pressure will be considerably greater than collateral pressure. If this is not the case then the resistance measured must inevitably be inaccurate. At the highest flow rates again the resistances become similar. There are two possible explanations for this. Firstly it may be that there are inadequate numbers of observations at the high flow rates. Secondly it might be that when the flow rate is unphysiologically high all the blood vessels in the limb distal to the infusion become maximally dilated and that normally closed or very small vessels open up to accommodate the enhanced flow. If this were the case resistance would reflect the end arterial resistance made up by the arteriolar bed. This resistance is likely to be the same irrespective of the severity of the disease present and would depend upon the bulk of tissue

being supplied by the artery under study. At 38 - 81 ml/min however it is possible to separate the femoropopliteal from the two other groups both of which have a significantly higher resistance. At 117 ml/min the resistance of the femoropopliteal group was higher than the femorotibial group. The numbers in the femorotibial group were small but this alone is not enough to account for this finding. The most likely explanation is that the femoropopliteal group had a higher resistance as a result of having poorer runoff relative to the femorotibial group. Resistance will be compared with runoff later in this chapter. It is interesting that the resistance of the femorotibial and amputation groups is the same. This indicates that the severity of disease in the two groups is similar, and the results achieved in the femorotibial group (Figure 51) would support this suggestion. The conflicting results achieved at 38/45 ml/min and 76/81 ml/min are hard to explain, particularly the fact that the femoropopliteal resistance is significantly higher than the femorotibial resistance at 45 ml/min. The pooling of results for the two flow rates is inevitably a compromise but in future the combined results will continue to be quoted.

In conclusion resistance is higher where the disease is more severe, but the flow rate at which

resistance is measured is important to permit this differentiation. In the data presented the available runoff was very variable and this might be reflected in some of the anomalous results. In subsequent sections data analysis will concentrate upon the findings at 38/45 ml/min and 76/81 ml/min.

Section 3

POST PAPAVERINE RESISTANCE

INTRODUCTION

It has been suggested extensively in the literature that all haemodynamic measurement in peripheral vascular surgery should be performed under conditions of maximal vasodilatation. This it is argued will remove the error induced by having a partially vasoconstricted vascular tree and will allow comparisons to be made between patients. For the majority of the patients in the femoropopliteal group but excluding the first six, resistance has first been measured under resting conditions, and then under maximal vasodilatation induced by intra-arterial papaverine. No such measurements were made in the femorotibial or amputation groups. Resistance has been measured at the combined flow of 76/81 ml/min, 117 ml/min and 153 ml/min. In each case the resistance was first measured at 76/81 ml/min and the lowest pressure reached after injection of papaverine was recorded. When the pressure had reached its trough at 76/81 ml/min the flow was changed.

The aim of this section was to examine the post papaverine resistances and to compare them with the

pre papaverine levels.

RESULTS

The results are shown in Table 6 in the Appendix (pages D14-16) and are summarised in Figure 45. The differences between the resistances at the three flow rates both pre and post papaverine are shown below. Resistance at 76/81 ml/min was higher than at 117 or 153 ml/min but there was no significant difference between 117 and 153 ml/min. At each flow rate resistance pre papaverine was significantly higher than post papaverine.

Flow	**76/81**	**SE**	**117**	**SE**	**153**	**SE**	**ml/min**
Pre pap Res	986	68	761	68	673	68	
p <	0.0001		0.0001		0.0001		
Post pap Res	597	66	402	70	457	102	

^-- p<0.001 --^

^-------- p<0.02 ---------^

^-- N/S --^

FEMOROPOPLITEAL GROUP - POST-PAPAVERINE RESISTANCE

Flow	76/81	117	153 ml/min
	719	461	1124
	562	384	575
	1256	350	209
	759	273	509
	1178	230	130
	580	299	235
	395	555	529
	456	341	444
	617	239	1509
	395	205	418
	370	170	130
	271	495	222
	246	188	261
	666	410	366
	271	1811	196
	518	547	
	1925	470	
	518	153	
	444	290	
	197	307	
	493	470	
	382	256	
	543	358	
	296		
	691		
	530		
	1111		
	543		
	419		
	580		
Mean	597	402	457
SE	66	70	102

Figure 45

DISCUSSION

As has previously been shown the resistance in general decreases as the flow increases. However there was no difference between the resistance measured at 117 ml/min and 153 ml/min. This lack of difference is artefactual and is due to the properties of papaverine. The duration of action of the papaverine is short so that by the time the pressure has reached its trough for the first flow rate the papaverine effect was already wearing off. This has the effect of artificially lowering resistance measured at the early flow rates in relation to the later readings, and explains why the resistance measured at 117 ml/min is lower than that measured at 153 ml/min. If the post-papaverine results are to be used for subsequent analysis then repeated injections of papaverine will be required. The comparison between pre and post-papaverine resistances shows that even though the papaverine was wearing off the resistance was still lower than prior to its administration. For each flow rate the difference was significant. For subsequent sections of this chapter the post-papaverine results will only be examined at 76/81 ml/min since this was the flow which was always measured first in the sequence of flow rates.

Section 4

RESISTANCE AND RADIOLOGICAL RUNOFF

INTRODUCTION

In this section a detailed examination of resistance in relation to radiological runoff will be made. One would expect from the previous sections, which have shown that resistance correlates with the severity of disease defined by the type of operation, that the resistance should correlate with radiological runoff. The runoff has been studied in two ways. The first method is that which is usually used in reports in the journals (Koontz and Stansel 1972) to separate groups of patients by the severity of disease. The patients are split up according to the number of vessels patent in the calf. This method is inaccurate because it is usually not clear whether the vessel must be fully patent from top to bottom into the foot, whether a short segment of patent vessel in the calf counts as patent, whether connection to the foot by collaterals counts as a patent vessel, or how important is full connection to the popliteal artery. In most patients some part of all three vessels is patent below the knee on intraoperative arteriography, but these patients are

not usually considered to have three vessel runoff. The second method of assessment takes into account these problems by defining runoff in a more comprehensive way. Each vessel below the knee is scored according to the degree of narrowing in it; 1= normal; 2= mild atheroma; 3= severe atheroma; and 4= blocked. The popliteal artery above the anastomosis is also scored to give some idea of how good the proximal runoff is. The popliteal artery has been scored with the same scoring system as used for the individual calf vessels. The anastomosis between graft and artery is also scored; 1= excellent; 2= mildly narrowed; and 3= severely narrow. Finally the number of vessels patent to the ankle has been noted; 1= 3 vessels patent; 2= 2 vessels patent; 3= 1 vessel patent. In both the first and second methods the patency of individual vessels in the calf has been counted as present if the vessel is patent no matter how narrow it may be.

METHOD

Using the above methods of scoring the runoff has been objectively defined for each of the patients in the femoropopliteal group. The maximum score possible for the first method is three with a minimum of zero whilst for the second the maximum score was 23 with a minimum of 6. The resulting score has been compared with the

resistance measured at 38/45 ml/min, 76/81 ml/min, 117 ml/min, and 153 ml/min.

RESULTS

The main results are summarised in Figure 46. In this table patient (Pat No), comprehensive runoff (CRO), simple runoff score (RO), and resistance at the specified flow rates, have been given. The last two columns of resistance values are the measurements after papaverine. Figure 48 shows the raw data for the comprehensive runoff score.

The combined results are detailed in Figure 47. Correlation using the Spearman Rank Correlation test is shown together with level of significance for each column. As can be seen the correlation is poor using the simple estimate of runoff but significant using the comprehensive runoff score. Interestingly the correlation between the two methods of evaluation of the arteriogram is fair r = 0.8844. At 81 ml/min it is probable that the poor correlation with simple runoff score is partly artefactual and due to the number of tied scores.

The results have also been analysed by listing resistance by flow rate split up according to the runoff. For the simple runoff (RO) this is by number of

vessels patent to the foot. For the comprehensive runoff the patients have been arbitrarily divided into three groups. Group one had a score of 6-11, group two had a score of 12-16, and group three had a score of 17-23.

The results for the RO group are summarised in Figure 49. Before papaverine there were no significant differences between the adjacent groups except at 45, 81, and 153 ml/min the resistance for three vessel runoff (score one) was significantly lower than that for the single vessel group (score three) ($p<0.05$). After papaverine there were significant differences in resistance between adjacent groups with one exception.

The results for the CRO group are summarised in Figure 50. With the exception of one measurement there were no significant differences at all. The mean resistance did however generally increase with increasing severity of disease. The post-papaverine results in this case also showed no significant differences.

FEMOROPOPLITEAL GROUP - RESISTANCE VS. RUNOFF

Pat No	CRO	RO	45	81	117	153	Post Pap 81	117
1	16	3	1250	1210				
3	17	3	2020	1380		843		
4	18	3	1140	888		530		
7	15	2	759	615		592	719	
8	18	3	968	667		486	562	
9	20	3	2610	2240		1780	1256	
10	11	1	2380	1500		987	759	
11	20	3	3130	1575			1178	
12	17	2	977	740	641	549	567	
13	13	1	1040					
15	9	1	1350	666	520		580	461
16	10	1	1777	1086	760	660		384
18	11	1	1522	981	730	558	395	273
19	17	3	1244	913	663			230
20	16	3	1577	1148	931	712	456	299
21	17	2	800	580	461	379	617	555
22A	9	1	1130	618		392		
22B	13	2	711	567	452		395	341
23	9	1	1022	728	512	405	370	239
24	15	1	866	641	495	385	271	205
25	11	1	733	493	358	294	246	170
26	11	1	1688	1209	957	810	666	495
27	11	1	1155	950	743	549	271	188
28	17	2	1822	1259	1025	895	518	410
29	16	2	2844	2123	1641	1568	1925	1811
30	20	3	2044	1432	1145	967		
31B	16	2		901			444	470
33B	12	1	1200	765	598	470	382	307
34	19	3	1377	1000	760	620	543	470
35	17	3	2688	1913	598	1274		
36	18	3	755	469	393	359	296	256
37	15	2		962				
38A	20	3	1355	1074	982		530	
38B	19	3		802				
39	18	2		1037			543	
40	16	2		592			419	358

Figure 46

FEMOROPOPLITEAL GROUP - RESISTANCE VS. RUNOFF

Correlation between RO_{γ} CRO_{γ} and Resistance

	RO		CRO	
	Rho	P	Rho	P
Pre papaverine				
45 ml/min	-2008	N/S	0.775	<0.01
81 ml/min	-727	N/S	0.807	<0.01
117 ml/min	-1026	N/S	0.626	<0.01
153 ml/min	-810	N/S	0.696	<0.01
Post papaverine				
81 ml/min	-560	N/S	0.705	<0.01
117 ml/min	-588	N/S	0.589	<0.01

All tests - Spearman Rank correlation test

Figure 47

FEMOROPOPLITEAL GRAFTS

NAME	POP	AT	PT	PN	ANAST	PATENT TO ANKLE	RESISTANCE VESSELS
01	2	3	4	2	2	1	TPT
02	N	4	1	4	N	1	TPT
03	4	3	4	2	1	1	POP
04	4	1	4	4	2	1	POP
05	N	1	1	1	N	3	N
06	1	2	1	4	1	2	POP
07	4	3	2	3	1	2	POP
08	2	4	3	4	2	1	POP
09	3	4	4	3	3	1	POP
10	4	1	1	3	1	3	POP
11	4	4	4	3	2	1	TPT
12	4	2	2	4	3	2	POP
13	1	3	3	3	2	3	TPT
14	3	4	1	2	1	2	POP
15	2	2	1	2	1	3	POP
16	4	1	1	2	1	3	POP/AK
17	-	-	-	-	-	-	-
18	2	1	3	3	1	3	POP
19	4	3	4	2	1	1	POP
20	3	3	3	3	1	1	TPT
21	4	4	3	2	2	2	TPT
22A	4	1	1	1	1	3	POP/AK
22B	3	1	2	3	2	2	TPT

Figure 48

NAME	POP	AT	PT	PN	ANAST	PATENT TO ANKLE	RESISTANCE VESSELS
23	4	1	1	1	1	3	POP/AK
24	4	2	3	3	2	3	POP
25	4	1	1	2	2	3	POP/AK
26	4	1	1	3	1	3	POP/AK
27	4	1	1	2	2	3	POP/AK
28	4	3	3	3	2	2	TPT
29	4	1	4	2	3	2	POP
30	4	4	4	3	2	1	TPT
31A	3	2	4	3	N	2	POP
31B	4	4	3	3	1	1	POP
32	-	-	-	-	-	-	-
33A	-	-	-	-	-	-	-
33B	4	3	1	2	1	3	POP/AK
34	4	4	4	2	2	1	TPT
35	4	4	1	4	1	1	TPT
36	4	4	2	4	1	1	TPT
37	3	2	4	3	1	2	TPT
38A	4	4	4	3	2	1	TPT
38B	4	4	4	3	1	1	TPT
39	4	4	3	3	2	2	TPT
40	4	2	4	2	2	2	POP

Score 1 - Normal
2 - Mild
3 - Severe
4 - Blocked

Patent = At least 4 inches
Anast 1 - Excellent
2 - Narrowed
3 - Badly narrowed

Popliteal 1 - Good
2 - Moderate
3 - Poor
4 - Blocked

TPT - Tibioperoneal trunk
N - Not known
Pop - Popliteal artery; AK - Above knee; BK - Below knee

Figure 48

FEMOROPOPLITEAL GROUP - RESISTANCE VS. RUNOFF

Conventional assessment - Arteriogram score

Vessels	One	P	Two	P	Three	P (1 vs. 3)
Pre papaverine						
45 ml/min						
Mean Res	1225	N/S	1470	N/S	1704	<0.05
SE	104		357		211	
No.	11		7		13	
81 ml/min						
Mean Res	813	N/S	988	N/S	1193	<0.025
SE	76		152		133	
No.	10		11		14	
117 ml/min						
Mean Res	630	N/S	844	N/S	781	N/S
SE	64		251		104	
No.	9		5		7	
153 ml/min						
Mean Res	502	N/S	828	N/S	841	<0.05
SE	56		190		158	
No.	9		6		9	
Post papaverine						
81 ml/min						
Mean Res	397	0.047	690	N/S	688	0.047
SE	57		150		151	
No.	8		10		7	
117 ml/min						
Mean Res	302	<0.05	657	0.04	313	<0.05
SE	42		254		61	
No.	9		6		4	

Figure 49

FEMOROPOPLITEAL GROUP - RESISTANCE VS. RUNOFF

Comprehensive runoff score

	6-11	P	12-16	P	17-23	P (Col1-Col3)
Pre papaverine						
45 ml/min						
Mean Res	1417	N/S	1569	N/S	1400	N/S
SE	173		217		262	
No.	9		14		8	
81 ml/min						
Mean Res	914	N/S	1084	N/S	1014	N/S
SE	113		129		155	
No.	9		16		10	
117 ml/min						
Mean Res	654	N/S	682	N/S	929	N/S
SE	82		86		230	
No.	7		9		5	
153 ml/min						
Mean Res	581	N/S	742	N/S	847	0.01
SE	87		141		216	
No.	8		11		5	
Post papaverine						
81 ml/min						
Mean Res	469	N/S	636	N/S	657	N/S
SE	81		109		197	
No.	7		10		8	
117 ml/min						
Mean Res	315	N/S	343	N/S	570	N/S
SE	53		79		224	
No.	7		5		7	

Figure 50

DISCUSSION

Of the two methods used to assess the runoff arteriographically the comprehensive method is, not surprisingly, better than the conventional method. When the mean resistance was calculated according to the number of patent vessels in the calf using the conventional score there was a trend towards higher resistance with fewer vessels patent at each flow rate though this was not significant in each case. The same trend was seen with the three groups divided up by the comprehensive runoff score but the results were less convincing. This is presumably because of the way the cut off points were chosen. Whilst it would have been reassuring to find a good correlation between runoff and resistance it is not surprising that it has not been the case. The assessment of runoff does not take into account the actual size of the vessels, or the number and quality of collateral vessels. Correlation with patency is the key measurement by which the two methods must be assessed.

Section 5

RESISTANCE AND GRAFT PATENCY

INTRODUCTION

The most important part of this thesis is to discover whether resistance measurement is able to predict the likely outcome of a bypass operation. In this fifth section patency has been assessed and compared with the resistance measured preoperatively. The results are available for both the femorotibial and femoropopliteal groups. The minimum follow up period is eight months though only three grafts had a follow up of less than one year. Presentation of the results is not simple because a considerable number of the grafts remain patent. The small numbers in the post-papaverine group make analysis impossible though the results are presented for completeness.

RESULTS

As a group the femorodistal grafts remained patent for a median of only 1.0 months. Femoropopliteal graft patency was more difficult to assess because a proportion of the grafts were still patent at the time

of writing. The mean patency time of those grafts which had occluded was 5.89 months. If the whole group was included then mean patency was greater than 10.4 months. By whichever method femoropopliteal patency was assessed it was significantly better than the femorotibial group; $p<0.00003$ for the entire femoropopliteal group and $p<0.007$ for the occluded femoropopliteal group. These differences will obviously increase with time.

1. FEMOROTIBIAL GROUP

For the femorotibial group patency rates are summarised in Figure 51. None of these grafts except one remained patent for more than a few months. The minimum follow up period was four months. Resistance of those grafts surviving less than one month has been compared with those patent in excess of one month and the results are shown in Figure 52. There were no significant differences between the groups at any of the three flow rates measured.

FEMOROTIBIAL GRAFTS - GRAFT PATENCY (Months)

NAME	PATENCY
01	3.5
02	0.13
03	4.5
04	0.5
05	1.5
06	1
07	0.16
08	0.3
09	1
10	5
11	0.56
12	24 *
13	0.0
14	4.5
15	0.03
16	0.06
17	2.75
18	0.2
19	4 **
20	4

* - Indicates graft still patent at time of writing
** - Indicates patient died with a functioning graft

Figure 51

FEMOROTIBIAL GRAFTS - PATENCY

PRE PAPAVERINE

	< One month			> One month			
flow	45	81	153	45	81	153	ml/min
	3120	1990	784	911	641	352	
	1727	1650	738	3760	2380	790	
	2853	2486	732	2905	2610	614	
	5625	3599		10314	950		
	3455	3036		1111	691		
	2329	1518		888			
	1832	1204					
	4973	3376					
	777	740					
	1377	1012					
Mean	2806	2061	751	3314	1454	585	
SE	517	338	19	1622	480	155	
No	10	10	3	6	5	3	

There were no significant differences in resistance at any of the flow rates.

Figure 52

DISCUSSION

The results in this group are uniformly poor. All but three of the patients went on to amputation immediately after the graft failed, and as has already been shown the resistance in this group is no different to that measured in the amputation group. It is not surprising that there were no significant differences in this situation. Analysis of the results over a longer period was not possible for obvious reasons, and one may conclude that based on these results there is no justification doing the operation in patients with such severe disease.

2. FEMOROPOPLITEAL GROUP

For the femoropopliteal group the graft patency rates are summarised in Figure 53. Three patients with four grafts died with patent grafts, and sixteen grafts in fourteen patients were still patent at the time of writing. At one month, three months, six months, and twelve months resistance in patients with patent grafts has been compared in those with blocked grafts. Patients dying with a patent graft have been excluded.

Pre-papaverine

a. **One month.** The majority of grafts were patent (87.5%) and the resistances are shown in Figure 54. Mean and standard error are shown at the bottom of each column. At each flow rate the patent grafts had a significantly lower resistance than the blocked grafts. At 45ml/min $p<0.01$; at 81ml/min $p<0.01$; and at 117ml/min $p<0.02$.

b. **Three months.** More of the grafts had occluded (83% patent) but the differences were still significant at each of the flow rates (Figure 55); at 45ml/min $p<0.005$; at 81ml/min $p<0.005$; at 117ml/min $p<0.02$; and at 153ml/min $p<0.005$.

c. **Six months.** 67.5% of the grafts were still patent. The resistances are shown in Figure 56. At 81 and 153ml/min there were significant differences between the

FEMOROPOPLITEAL GRAFTS - GRAFT PATENCY

NAME	PATENCY	NAME	PATENCY	NAME	PATENCY
01	6	19	6	34	0.5
02	8	20	14	35	3
03	36 *	21	7	36	15 *
04	18 *	22a	10	37	11 *
05	9	22b	3	38a	15 **
06	0.13	23	16 *	38b	4 **
07	3 **	24	21 *	39	4
08	2	25	15*	40	8
09	0.1	26	19 *		
10	1.5	27	5		
11	0.1	28	7		
12	0.5 **	29	0.3		
13	30 *	30	3		
14	21 *	31a	14 *		
15	8	31b	8 *		
16	27 *	32	16 *		
17	5	33a	18 *		
18	12	33b	10 *		

* - Still patent at time of writing
** - Died with a functioning graft

Figure 53

FEMOROPOPLITEAL GROUP - RESISTANCE AT ONE MONTH

PRE PAPAVERINE

	< One month			> One month		
Flow	45	81	117	45	81	117ml/min
	968	667	486	1250	1210	352
	2610	2240	1780	921	552	843
	2380	1500	987	2020	1380	530
	3130	1575	1568	1140	888	289
	2844	2123	620	916	511	592
	1377	1000		759	615	660
				1040	666	300
				1350	1086	558
				1777	469	712
				711	981	379
				1522	913	392
				1244	1148	452
				1577	580	405
				800	618	385
				1130	567	294
				711	728	810
				1022	641	549
				866	493	895
				733	1209	967
				1688	950	777
				1155	1259	483
				1822	1432	614
				2044	1296	470
				1911	901	1274
				1200	913	359
				1600	987	
				1200	765	
				2688	1913	
				755	469	
				1355	962	
					1074	
					802	
					1037	
					592	
Mean	2218	1517	1088	1296	900	573
SE	383	274	285	90	57	50

At each flow rate patent grafts had a significantly lower resistance than occluded grafts.

Figure 54

FEMOROPOPLITEAL GROUP - RESISTANCE AT THREE MONTHS

PRE PAPAVERINE

	< Three months				> Three months			
Flow ml/min	**45**	**81**	**117**	**153**	**45**	**81**	**117**	**153**
	968	667	641	1780	1250	1210	520	843
	2610	2240	1145	987	921	552	760	530
	2380	1500	760	549	2020	1380	367	289
	3130	1575	1598	1568	1140	888	730	660
	977	740	1641	967	916	511	663	300
	2844	2123		620	1040	666	931	558
	2044	1432		1274	1350	1086	461	712
	1377	1000		486	1777	469	452	379
	2688	1913			711	981	512	392
					1522	913	495	405
					1244	1148	358	385
					1577	580	957	614
					800	618	743	470
					1130	567	1025	359
					711	728	893	294
					1022	641	649	810
					866	493	752	549
					733	1209	598	895
					1688	950	393	777
					1155	1259	982	483
					1822	1296		
					1911	901		
					1200	913		
					1600	987		
					1200	765		
					755	469		
					1355	962		
						1074		
						802		
						1037		
						592		
Mean	2113	1465	1157	1028	1237	859	662	535
SE	289	202	230	169	76	49	49	44

At each flow rate patent grafts had a significantly lower resistance than occluded grafts.

Figure 55

FEMOROPOPLITEAL GROUP - RESISTANCE AT SIX MONTHS

PRE PAPAVERINE

	< Six months			> Six months			
Flow 45 ml/min	81	117	153	45	81	117	153
968	667	367	486	1040	666	520	660
2610	2240	452	1780	1350	1086	760	843
2380	1500	743	987	1777	1210	730	530
3130	1575	1641	300	1250	552	663	289
711	469	1145	549	921	1380	931	558
711	567	760	1568	2020	888	461	712
1155	950	1598	967	1140	511	512	379
2844	2123		620	916	981	495	392
2044	1432		1274	1522	913	358	405
1377	1000			1244	1148	957	385
2688	1913			1577	580	1025	294
	1037			800	618	893	810
				1130	728	649	895
				1022	641	752	777
				866	493	598	483
				733	1209	393	614
				1688	1259		470
				1822	1296		359
				1911	901		
				1200	913		
				1600	987		
				1200	765		
				755	469		
					962		
					592		
Mean 1874	1289	958	947	1281	869	668	547
SE 287	181	210	180	108	79	53	47

At 81 and 153 ml/min patent grafts had significantly lower resistance than occluded grafts.

Figure 56

FEMOROPOPLITEAL GROUP - RESISTANCE AT TWELVE MONTHS

PRE PAPAVERINE

	< Twelve months			> Twelve months			
Flow ml/min	**45**	**81**	**117**	**153**	**45**	**81**	**117**	**153**
	1250	1210	520	289	2020	1380	760	843
	921	554	367	486	1140	888	730	530
	916	511	663	1780	1040	1086	931	660
	968	667	461	987	1777	981	512	558
	2610	2240	452	300	1522	1148	495	712
	2380	1500	753	379	1577	728	358	405
	3130	1575	1025	392	1022	641	957	385
	1350	666	1641	549	866	493	893	294
	711	469	1145	895	733	1209	649	810
	1244	913	760	1568	1688	1296	752	777
	800	580	1598	967	1911	913	598	483
	1130	618		620	1200	987	393	614
	711	567		1274	1600	765	982	470
	1155	950			1200	469		359
	1822	1259			755	962		
	2844	2123				1074		
	2044	1432						
	1377	1000						
	2688	1913						
		1037						
		592						
Mean	1581	1065	853	491	1336	938	693	564
SE	186	122	141	141	111	68	61	48

There were no significant differences in resistance at twelve months at any of the flow rates.

Figure 57

two groups ($p<0.02$ and $p<0.025$ respectively) but at 117ml/min there was no significant difference. At 45ml/min the difference approached significance ($p=0.0594$).

d. **Twelve months.** There were approximately equal proportions of patent and occluded grafts and the resistances are shown in Figure 57. There were no significant differences between the two groups at this stage at any of the flow rates, and at 153 ml/min the resistance in the patent group was higher than the occluded group.

To be most useful it should be possible to choose a level of resistance below which a graft would have a reasonable chance of success and above which an alternative procedure would be more appropriate. Patency time has been studied above and below four critical resistance levels, 800, 1000, 1200, and 1500mPRU. Resistance at 81ml/min has been chosen because overall this flow has produced the most encouraging results to date. The results are shown in Figure 58. There were significant differences in patency at 1000 ($p<0.05$), 1200 ($p<0.05$),and 1500mPRU ($p<0.01$), but not at 800mPRU. All grafts were included in this analysis except those in which there had been death with patency. If the grafts still patent were excluded then there were still

FEMOROPOPLITEAL GROUP - PATENCY BY RESISTANCE LEVEL

PRE PAPAVERINE - 81 ML/MIN

Patency in months

Res - mPRU							
<800	>800	<1000	>1000	<1200	>1200	<1500	>1500
8	6	8	6	8	6	6	36
9	36	18	36	18	36	8	0.1
2	18	9	0.1	9	0.1	18	1.5
8	0.1	2	1.5	2	1.5	9	0.1
5	1.5	8	0.1	8	0.1	2	0.3
7	0.1	5	27	27	19	8	3
10	27	12	14	5	7	27	
3	12	6	3	12	0.3	5	
16	6	7	19	6	3	12	
21	14	10	7	14	14	6	
15	19	16	0.3	7	3	14	
10	5	21	3	10		7	
15	7	15	14	3		10	
8	0.3	5	0.5	16		3	
	3	8	3	21		16	
	14	16	4	15		21	
	8	18		5		15	
	16	10		8		19	
	18	15		16		5	
	0.5	11		18		7	
	3	8		10		3	
	4			0.5		14	
	11			15		8	
				11		16	
				4		18	
				8		10	
						0.5	
						15	
						11	
						4	
						8	
M 9.78	9.97	10.85	8.65	10.63	8.18	10.5	6.83
SE 1.46	1.98	1.13	2.75	1.26	3.49	1.41	6.4

Figure 58

significant differences at the resistance levels already documented; at 1000mPRU $p=0.01$; at 1200mPRU $p<0.025$; and at 1500 mPRU $p<0.01$ (Figure 59).

POST-PAPAVERINE

Resistance was measured in each case at 81 ml/min prior to its measurement at the other flow rates. A similar correlation between resistance and patency has been calculated after papaverine as has been calculated for the correlation prior to papaverine. At each time interval patent grafts had a significantly lower resistance than occluded grafts; at one month $p<0.005$; at three months $p<0.001$; at six months $p<0.05$; and at twelve months $p<0.01$ (Figure 60). When comparing patency rates for a given resistance cut off level different resistance levels were chosen; 400, 500, and 700 mPRU. Patients with a resistance less than 400 mPRU had a significantly longer patency than those with a resistance greater than 400 mPRU $p<0.05$. The same was true at 500 mPRU $p<0.01$ and 700 mPRU $p=0.001$ (Figure 61). If the grafts remaining patent were excluded then the differences were no longer significant at 400 mPRU but remained so at 500 mPRU $p=0.01$ and 700 mPRU $p<0.01$ (Figure 62).

FEMOROPOPLITEAL GROUP - PATENCY BY RESISTANCE LEVEL

PRE PAPAVERINE - 81 ML/MIN - Excluding still patent grafts

Patency in months

Res - mPRU	<800	>800	<1000	>1000	<1200	>1200	<1500	>1500
	8	6	8	6	8	6	36	6
	9	36	18	36	18	36	8	0.1
	2	18	9	0.1	9	0.1	18	1.5
	8	0.1	2	1.5	2	1.5	9	0.1
	5	1.5	8	0.1	8	0.1	2	0.3
	0.1	7	5	14	5	7	8	3
	10	12	12	3	12	0.3	5	
	3	6	6	7	6	3	12	
	8	14	7	0.3	14	3	6	
		5	10	3	7		14	
		7	5	0.5	10		7	
		0.3	8	3	3		10	
		3		4	5		3	
		0.5			0.5		5	
		3			4		7	
		4			8		3	
							0.5	
							4	
							8	
Mean	6.66	7.28	8.16	6.03	7.46	6.33	7.13	6.83
SE	0.96	2.39	1.21	2.82	1.16	4.03	1.00	6.39

Figure 59

FEMOROPOPLITEAL GROUP - RESISTANCE IN MONTHS

POST PAPAVERINE - 81 ML/MIN - All cases

Time - months

	<1/12	>1/12	<3/12	>3/12	<6/12	>6/12	<1yr	>1yr
	1256	562	562	580	562	580	562	384
	1178	759	1256	384	1256	384	1256	395
	1925	580	759	350	759	395	759	456
	543	384	1178	395	1178	456	1178	370
		350	1925	456	350	617	350	271
		395	543	617	395	370	617	246
		456		395	271	271	395	666
		617		370	1925	246	271	518
		395		271	543	666	518	197
		370		246	543	518	1925	493
		271		666		518	543	296
		246		271		444	543	
		666		518		197	419	
		271		518		493		
		518		444		382		
		518		197		296		
		444		493		691		
		197		382		419		
		493		296				
		382		691				
		296		543				
		691		419				
		543						
		419						
Mean	1225	450	1037	431	778	441	718	390
SE	326	30	236	29	173	34	134	43

At each time interval resistance in patent grafts was significantly lower than in the occluded grafts.

Figure 60

FEMOROPOPLITEAL GROUP - PATENCY BY RESISTANCE LEVEL

POST PAPAVERINE - 81 ML/MIN - All cases

Patency in months

Res - mPRU	<400	>400	<500	>500	<700	>700
	27	2	27	2	2	0.1
	5	0.1	5	0.1	8	1.5
	12	1.5	12	1.5	27	0.1
	6	0.1	6	0.1	5	0.3
	3	8	14	8	12	
	16	14	3	7	6	
	21	7	16	19	14	
	15	19	21	7	7	
	5	7	15	0.3	3	
	16	0.3	5	14	16	
	10	14	8	0.5	21	
	15	8	16	11	15	
		18	18	4	19	
		0.5	10		5	
		11	15		7	
		4	8		14	
		8			8	
					16	
					18	
					10	
					0.5	
					15	
					11	
					4	
					8	
Mean	12.58	7.2	12.43	5.73	10.8	0.5
SE	2.17	1.56	1.69	1.73	1.33	0.38

Figure 61

FEMOROPOPLITEAL GROUP - PATENCY BY RESISTANCE LEVEL

POST PAPAVERINE - 81 ML/MIN - Excluding still patent grafts

Patency in months

Res - mPRU	<400	>400	<500	>500	<700	>700
	5	2	5	2	2	0.1
	12	0.1	12	0.1	5	1.5
	6	1.5	6	1.5	12	0.1
	3	0.1	14	0.1	6	0.3
	5	14	3	7	14	
		7	5	7	7	
		7	8	0.3	3	
		0.3		0.5	5	
		0.5		4	7	
		4			0.5	
		8			4	
					8	
Mean	6.2	4.04	7.57	2.5	6.12	0.5
SE	1.71	1.41	1.64	1.00	1.17	0.38

Figure 62

DISCUSSION

There are inherent difficulties in comparing graft patency in two groups of patients when 36% of the grafts remain patent at the time of analysis. For this reason it was not possible to look at a straight correlation between resistance and patency. Clearly the longer a graft remains patent the more potential factors there are likely to lead to its occlusion. Pseudointimal hyperplasia (Beard and Fairgrieve 1986), progression of disease distally, continued smoking (Myers, King, Scott et al 1978), graft degeneration (Layer, King and Jamieson 1984),repeated kinking of the graft as it traverses the knee joint, or inadequate inflow (Charlesworth, Harris, Cave et al 1975) are all factors which affect graft patency to an increasing extent with time. The most significant differences in patency which are due to the runoff resistance at the time of grafting will therefore be felt to the greatest extent in the early postoperative period. Few grafts were available for analysis with a potential patency of more than 18 months but all grafts had a minimum follow up of eight months. At one and three months both before and after papaverine there were the most significant differences in resistance between patent and occluded grafts. Only in the post papaverine group were the

differences significant at one year. The majority of graft failures occur in the first twelve months (Cutler, Thompson, Kleinsasser et al 1976), and it would seem that resistance measurement is able to detect this group. After papaverine the comparison between patent and non-patent grafts has only been made at 81ml/min. As has previously been described, this was because the effect of papaverine was transient and the resistances measured at 117, and 153 ml/min were therefore not at maximal enhancement and essentially inaccurate. To be useful clinically the method should be able to differentiate grafts into patent and occluded groups by a cut off resistance level. Three of the four pre-papaverine resistance levels and all three post-papaverine resistance levels were able to demonstrate significant differences in patency. There was however overlap between the groups such that the differences might only be useful clinically when using a comparatively high cut off level which suffers from making the test less discriminating.

Section 6

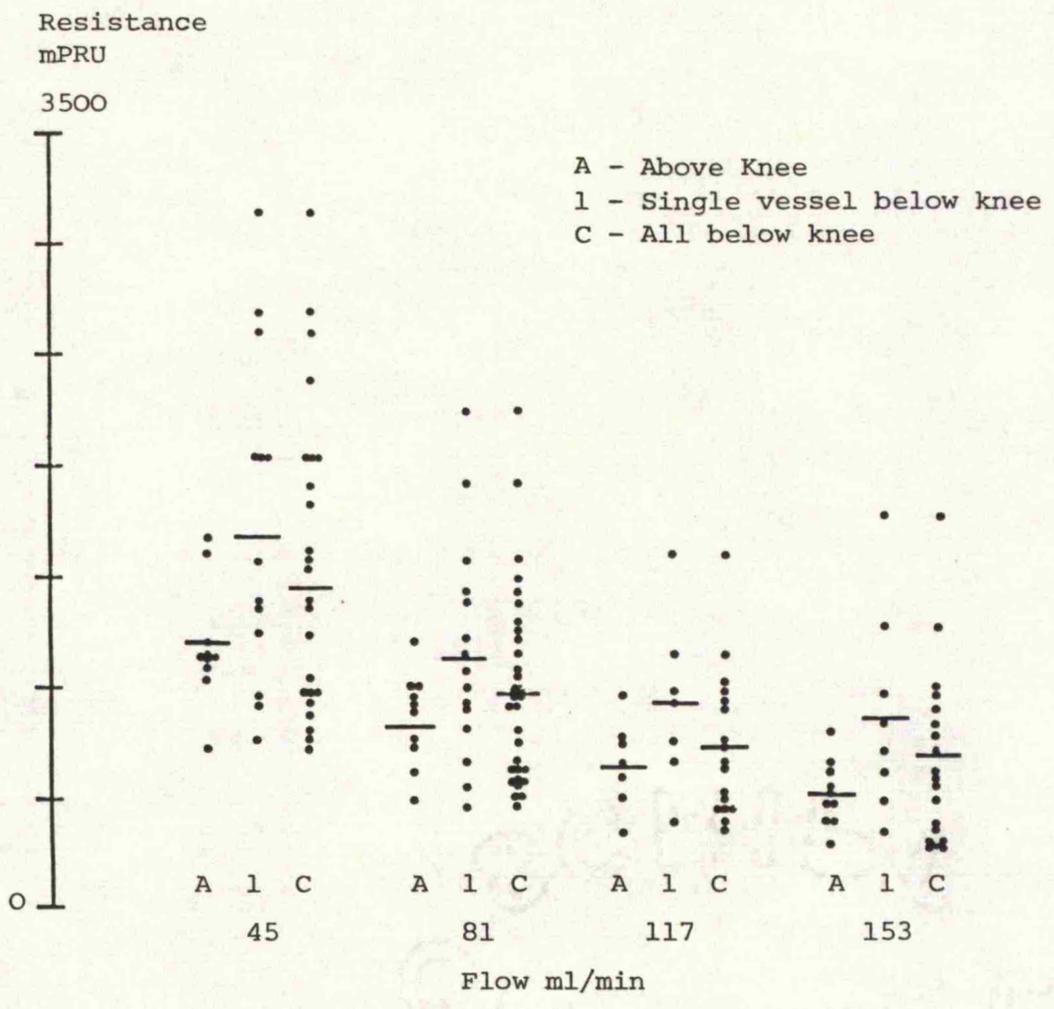
RESISTANCE AND SITE OF GRAFT INSERTION

INTRODUCTION

It is known that femoropopliteal reconstructions to the above knee popliteal artery have a longer patency than those placed beyond the knee. It might be expected that the resistance of the popliteal artery above the knee would be lower than that measured beyond the knee since the potential runoff is greater. In this group of forty four grafts there were ten placed above knee. In this section the resistance of this group has been compared with the rest and with the ensuing patency. All measurements have been made before the administration of papaverine.

RESULTS

Resistance has been measured at four flow rates; 45, 81, 117, and 153 ml/min. In each case all results for the above knee group have been grouped together regardless of arteriographic runoff. In the below knee group data has been presented in two ways. Firstly all the results have been put together in a single group,



Mean resistance - pre papaverine - femoropopliteal grafts

Significant differences in resistance only occur when comparing above knee and single vessel runoff groups.

Figure 63

and secondly data for single vessel runoff cases has been looked at separately. The results are shown in full in Table 7 and 8 in the Appendix (pages D17-18),and in Figure 63 where mean resistance is indicated by the horizontal bar. It can be seen that there were no differences between the two groups when all the below knee cases were included. However when only the single runoff cases were compared with the above knee group the differences were significant at all four flow rates; $p=0.05$ at 45 ml/min; $p<0.05$ at 81 ml/min; $p<0.05$ at 117 ml/min ; and $p<0.05$ at 153 ml/min. There were no differences between the above knee group and the two and three vessel runoff below knee group. The mean patency of the above knee group was 15.4 months (SE 1.91) and this was significantly longer than the below knee group 8.78 months (SE 1.59) $p<0.005$. Both groups contained patent grafts at the time of writing; the above knee group with 7/10 and the below knee group with 6/30.

DISCUSSION

Contrary to what might be expected these results indicate that there is no significant resistance advantage to grafting above knee except when the runoff below knee was very poor. In this series as in others (Charlesworth, Brewster, Darling et al 1985) the patency of above knee procedures was superior to that achieved below knee. It is possible that the use of artificial grafts might account for this difference but similar proportions of the above knee (6/10) and below knee (18/34) procedures were performed with artificial grafts suggesting that this is not in fact the case. There must be some inherent problem with grafts that have to cross a joint which results in their premature occlusion which has yet to be defined. Recent research suggests that for artificial grafts this factor might be the kinking which occurs at knee level when the knee is flexed.

SUMMARY TO CHAPTER 8

Resistance has been measured in three groups of patients, and a total of 77 limbs have been studied. At any one flow rate patients having femoropopliteal reconstruction had lower resistance than those having either amputation or femorotibial reconstruction. Interestingly there were no real differences between the two latter groups indicating the severity of disease in the femorotibial group. Indeed the results in the femorotibial group would suggest that they should have undergone primary amputation.

Within the femoropopliteal group resistance measurement was only able to separate all above knee grafts as a group from single vessel below knee grafts. Two and three vessel runoff grafts below knee did not have significantly different resistance levels. This is perhaps surprising given the differences in clinical outcome, even though the length of popliteal artery separating the two sites is only 10 cm.

The comparison between concentric and sidearm methods of resistance measurement confirmed that to use the simple sidearm method would require recalibration on each occasion.

Saline was used in a small group of patients in parallel with blood to measure resistance. The

correlation between it and blood was poor and as in the dog experiments saline failed to separate different runoffs as well as blood.

The comparison between resistance and runoff in the three operative groups showed that at low flow rates resistance was not a good predictor of runoff. At high flow rates there were only small numbers but again the discriminatory power of resistance was lost. There appeared to be a narrow window where resistance measurement was accurate. Previous work has suggested that a minimum flow of between 60 ml/min (Little, Shiel, Loewenthal et al 1968) and 100 ml/min (Cappelen and Hall 1967) is required to maintain longterm graft patency. Resistance measured at a flow somewhere in this range would therefore seem to be desirable. At the end of the study resistance was measured at the single flow rate of 81 ml/min. Within the femoropopliteal group the resistance was shown to correlate with a comprehensive assessment of runoff but not simply with the number of vessels patent in the calf.

In the femoropopliteal group where the highest number of results was available there was good correlation between patency and resistance both before and after papaverine. Resistance was however only a significant predictor upto nine months after grafting. It is not clear whether this was due to small numbers or

because of disease progression. Employing a cutoff resistance also resulted in a significant prediction of outcome at several of the flow rates tested.

To be useful, an assessment of runoff must allow the surgeon to make decisions as to whether reconstructive surgery is possible or whether he should proceed directly to amputation. The cut off levels shown in Figure 58 indicate that a level of resistance in excess of 1200 mPRU is generally associated with a very short graft patency and this may represent the area where resistance measurement might be most useful.

CHAPTER 9

CONCLUSIONS AND FUTURE PROSPECTS

Peripheral resistance measurement has been shown in the preceding chapters to correlate with disease severity in three groups of patients with widely differing types of disease. In a group of dogs with no vascular disease the resistance measured in each of the individuals was very similar, suggesting that the method was reproducible. Within any one of the groups of patients resistance correlated well with the comprehensive assessment of runoff defined arteriographically and would support the findings of Bliss (1973).

Resistance has been shown not to be constant but to vary with flow, being lower the higher the flow at which it is measured. This implies the need to measure resistance at a single flow rate in order to make comparisons between individuals, a fact not apparently noted by previous authors (Vetto and Dunphy 1964, Delin and Ekestrom 1965, Mundth, Darling, Moran et al 1969, and Bliss 1973). The relationship between resistance and severity of disease is, however, approximately constant

over a range of flows except when these are either very low or very high (Pappenheimer and Maes 1942 and Green, Lewis, Nickerson et al 1945).

Resistance measurement has also been shown to correlate with outcome in the femoropopliteal group, where higher resistance values were associated with shorter patency. Unlike previous authors, particularly Bliss (1973); Mundth, Darling, Moran et al (1969); and Barner, Kaminski, Codd et al (1974) it has been shown that if resistance at 81 ml/min is over 1200 mPRU the chances of prolonged graft patency are small. The fact that comparisons have been made at constant flow may account for these differences.

Despite trying three infusion solutions none had any significant advantage over blood. Saline was distinctly inferior because its low viscosity resulted in poor separation between different resistance loads. Dextran was more suitable having a viscosity similar to that of blood but it caused muscle fasciculation in the dog and by adding extra expense to the procedure carried no other significant advantages.

The role of papaverine is not clear from these experiments. Because of its short duration of maximal action its use is only suitable for resistance measurement at one flow rate. It resulted in a reduction in resistance peripherally in almost every case, but

the relationship to pre-papaverine measurements was not constant. Post-papaverine measurements, like the pre-papaverine measurements, correlated with outcome and therefore either set of measurements could have been used.

The early experiments required large quantities of blood so that resistance could be measured at a range of flow rates. As a result it has been shown that both low and high flow rates were unsuitable for resistance measurement and that the best separation of resistances was achieved at 81 ml/min. It can be concluded that it is possible to measure resistance at one flow rate and that this should be at approximately 80-120 ml/min. This means that less blood is required at each session speeding and simplifying the procedure.

Providing a suitable yardstick by which to judge resistance measurement is not easy. Arteriography, traditionally held to be the gold standard, has been shown to correlate with resistance when a comprehensive assessment of the arteriogram was made. The simple method of counting the number of patent vessels in the calf was not sufficient. The majority of surgeons do not make such a comprehensive assessment and almost all reports in the literature of graft patency are based on simple runoff. Resistance measurement must therefore stand or fall on its ability to be as good as

or better than arteriography in defining the outcome.

Resistance measurement might be expected to have influence over outcome for a limited period because other factors will have an increasing influence the longer the life of the graft. These will affect the predictive power of both resistance measurement and arteriography. This study has suggested that resistance exerts its main influence in the first year of a grafts life, though numbers for comparison beyond one year are small.

Resistance measurement, unlike arteriography cannot be used to detect technical errors on the part of the surgeon except where these are gross. Some early failures in this series were certainly due to technical problems but because all the measurements have been included results are less significant than they might have been. It is not uncommon for authors reporting the results of reconstructive surgery to omit failures that occur in the first 30 days as technical failures. This manoeuvre undoubtedly favours arteriography as a means of judging results in these papers since apparently favourable pre reconstruction films would have been associated with early occlusion. No such exclusions were made in this work.

Even if both resistance measurement and arteriography were equally able to predict outcome there

would still be an advantage to using resistance measurement. In the first place direct comparison between patients in any one centre or between different centres becomes possible. The principle advantage of this is that standardisation of reporting of results might be achieved. Secondly sensible treatment regimens might be produced. It might be possible to save the patient, who will inevitably finish with an amputation within a few months, from expensive and time consuming efforts at vascular reconstruction. Similarly it might allow a borderline group to be identified in whom some procedure other than simple femoropopliteal reconstruction should be tried. Such alternatives include the use of adjunctive arteriovenous fistula, multiple sequential grafts or adjunctive extended profundaplasty.

The postoperative flow measurements in the graft have not been included. Because these were generally far in excess of the flows used to measure resistance, comparison and correlation between the two methods of prognosis prediction was not possible.

Though it would be easier to measure the pressure using the sidearm technique it has been shown to be inaccurate in practice both in the animal and human situation. The concentric cannula is undoubtedly easier to use and produces cleaner data than the direct needle.

The direct needle also carries the risk of damage to the atheromatous lining of the artery. Commercially available double lumen cannulae are currently undergoing evaluation to streamline the method further.

FUTURE PROSPECTS

At the moment measurement of resistance is still rather cumbersome. Trained Medical Physics personnel are required in theatre and their equipment takes up a lot of space. With a Department of Trade grant I am currently building a portable module containing pump, pressure amplifier, and single channel chart recorder. This, it is hoped, will be within the price range of many vascular surgeons so that the longterm goal of comparisons of outcome between centres by resistance measurement may become a reality.

As with any research project more work is required both to clarify this project and in new areas. The new module will run at 100 ml/min, and a new set of standard resistance levels will need to be found. Resistance measurement after papaverine which has not been emphasised in this thesis, needs to be compared with non-papaverine measurement of resistance at a single flow rate. Resistance measurement in other areas, particularly the femoral artery, might be useful. The problem of management of combined segment disease - aortoiliac and femoropopliteal - remains unresolved. Resistance measurement at groin level might make it possible to answer the question of whether aortoiliac reconstruction alone or a combination of the two is

required. A new project addressing this question is in progress.

As usual in research, providing an answer to one question, rather than being an end in itself, merely leaves one pondering the answers to many more.

APPENDIX

Section A

In this section of the Appendix the raw data for the first animal experiments is shown. Against each flow arterial and venous pressure are tabulated with the resultant resistance. In each case two sets of measurements have been performed and these are shown as Run 1 and Run 2. Flow is measured in ml/min, pressure is measured in mmHg and resistance is measured in mPRU.

DOG 1

	FLOW	ARTERIAL	VENOUS	RESISTANCE
Run 1	9.5	17	7.5	996
	19.1	20	7.8	637
	38.2	25	7.5	458
	76.4	33	7.8	330
	190	50	7.9	222
Run 2	9.5	17	8.0	943
	19.1	19	7.8	585
	38.2	25	8.7	445
	76.4	32.5	8.0	321
	190	52	8.8	227

DOG 2

	FLOW	ARTERIAL	VENOUS	RESISTANCE
Run 1	9.5	-	-	-
	19.1	19	4.9	736
	38.2	24	5.1	495
	76.4	30	6.0	314
	190	45	10.5	182
Run 2	9.5	10	3.8	650
	19.1	15	3.9	579
	38.2	22	5.0	445
	76.4	30	5.5	321
	190	44	11.0	174

Table 1

DOG 3

	FLOW	ARTERIAL	VENOUS	RESISTANCE
Run 1	9.5	20	6.0	1470
	19.1	25	6.0	990
	38.2	30	6.0	630
	76.4	37.5	6.0	410
	190	57.5	6.2	270
Run 2	9.5	17	6.2	1130
	19.1	20	6.2	720
	38.2	26	6.2	520
	76.4	35	6.2	376
	190	56	6.4	261

DOG 4

	FLOW	ARTERIAL	VENOUS	RESISTANCE
Run 1	9.5	13	2.3	1120
	19.1	17.5	2.4	788
	38.2	25	2.6	586
	76.4	29	2.5	347
	190	42	2.4	208
Run 2	9.5	13.5	2.4	1160
	19.1	17	2.5	757
	38.2	22	2.5	511
	76.4	29	2.4	348
	190	43	2.3	214

Table 2

DOG 5

	FLOW	ARTERIAL	VENOUS	RESISTANCE
Run 1	9.5	18	3.4	1530
	19.1	22	3.5	968
	38.2	27	3.6	612
	76.4	35	3.4	413
	190	46	3.7	222
Run 2	9.5	16	3.4	1320
	19.1	19.5	3.5	840
	38.2	24.5	3.5	550
	76.4	31.5	3.6	370
	190	45.5	3.7	220

DOG 6

	FLOW	ARTERIAL	VENOUS	RESISTANCE
Run 1	9.5	19	5.7	1390
	19.1	21	5.7	798
	38.2	27	5.9	552
	76.4	38	5.8	422
	190	49	6.0	226
Run 2	9.5	15	5.8	964
	19.1	19	6.0	679
	38.2	24.5	5.8	490
	76.4	33	6.1	350
	190	49	6.1	226

Table 3

DOG 7

	FLOW	ARTERIAL	VENOUS	RESISTANCE
Run 1	9.5	13	3.8	964
	19.1	16	4.0	626
	38.2	21.5	4.4	448
	76.4	29	4.9	315
	190	44	5.2	199
Run 2	9.5	10	3.8	649
	19.1	14	4.0	522
	38.2	19	4.4	382
	76.4	27	4.9	289
	190	45	5.3	210

DOG 8

	FLOW	ARTERIAL	VENOUS	RESISTANCE
Run 1	9.5	12	5.1	723
	19.1	16.5	5.2	590
	38.2	22.5	5.3	450
	76.4	31	5.3	336
	190	55	5.5	260
Run 2	9.5	12	5.8	650
	19.1	15	5.7	485
	38.2	21	5.8	398
	76.4	30	5.7	318
	190	50	5.8	233

Table 4

DOG 9

	FLOW	ARTERIAL	VENOUS	RESISTANCE
Run 1	9.5	12	3.8	860
	19.16	16	4.8	585
	38.2	20	4.1	416
	76.4	26	4.7	279
	190	36	6.1	157
Run 2	9.5	11	4.0	734
	19.1	14	4.1	517
	38.2	18.5	4.6	364
	76.4	24	5.1	260
	190	36	6.2	157

DOG 10

	FLOW	ARTERIAL	VENOUS	RESISTANCE
Run 1	9.5	14	6.6	776
	19.1	18	6.5	600
	38.2	22.5	7.0	406
	76.4	28.5	7.6	274
	190	40.5	8.5	168
Run 2	9.5	14	7.1	723
	19.1	17	9.7	506
	38.2	22	7.5	379
	76.4	28.5	7.9	270
	190	41.5	9.1	170

Table 5

APPENDIX

Section B

In this section the raw results of the amputation group are listed. Patients are numbered 1-12. In the first column (COLL) collateral pressure is shown in mmHg. For each flow arterial and venous pressure and the calculated resistance are shown. Flow is measured in ml/min, pressure in mmHg and resistance in mPRU. Patient 4 had pressure measured in both the anterior tibial (AT) and posterior tibial (PT) arteries. All measurements were made without Papaverine.

AMPUTATION

NAME	COLL	FLOW	ARTERIAL	VENOUS	RESISTANCE
1	40	9.5	35	4	3265
		19.1	46	4	2200
		38.2	60	4	1465
		76.4	84	4	1050
		190	135	4	689
2	-	9.5	200	3.5	20680
		19.1	320	3.6	16565
		38.2	-	-	-
		76.4	-	-	-
		190	-	-	-
3	36	9.5	200	28	18020
		19.1	368	28	17740
		38.2	-	-	-
		76.4	-	-	-
		190	-	-	-
4 (AT)		9.5	120	6	11450
		19.1	200	5	10180
		38.2	-	-	-
		76.4	-	-	-
		190	-	-	-
(PT)		9.5	344	4	35640
		19.1	-	-	-
		38.2	-	-	-
		76.4	-	-	-
		190	-	-	-
5	84	9.5	136	16	12630
		19.1	230	18	11100
		38.2	280	18	3430
		76.4	384	15	4830
		190	-	-	-

Table 1

Cont...

AMPUTATION

NAME	COLL	FLOW	ARTERIAL	VENOUS	RESISTANCE
6	40	9.5	42	10	3350
		19.1	51	10	2140
		38.2	64	10	1410
		76.4	90	10	1050
		190	158	10	780
7	24	9.5	94	3.5	9530
		19.1	136	3.5	6940
		38.2	156	2	4030
		76.4	160	2	2070
		190	232	3	1200
8	12	9.5	15	10	526
		19.1	44	10	1780
		38.2	70	10	1570
		76.4	80	10	916
		190	80	10	368
9	68	9.5	144	4	14750
		19.1	188	4	9630
		38.2	244	4	6280
		76.4	400	4	5185
		190	-	-	-
10	52	9.5	104	12	9685
		19.1	112	12	5235
		38.2	120	12	2830
		76.4	134	12	1600
		190	-	-	-
11	20	9.5	-	-	-
		19.1	-	-	-
		38.2	22	10	314
		76.4	28	11	222
		190	33	12	110
12	40	9.5	52	14	4000
		19.1	-	-	-
		38.2	112	14	2565
		76.4	160	14	1910
		190	280	12	1410

Table 1

APPENDIX

Section C

In this section raw data for the second animal experiments are tabulated. Page C3 is concerned with the calibration of the sidearm cannula resistance. For each of the dogs numbered 11 - 14 resistance has been measured at four flow rates (Q). Pressure (P) and the consequent resistance (Res) are tabulated for each of the infusing solutions.

In the second section, pages C4 - C6, raw data concerning the comparison between different methods of pressure measurement are listed for each of the infusing fluids in turn. Two columns of concentric (Conc), sidearm (Side), and Stab pressure are shown each measured in mmHg.

In the third section, pages C7 - C9, raw data for the constant flow infusions are shown. Under each flow arterial (P), and venous (V) pressure, and resistance (Res) are shown. Results are detailed for each of the two runoffs both before and after ischaemia.

In the fourth section, pages C10 - C12, raw data for the constant pressure infusions are shown. Tables are divided by presence or absence of ischaemia and by runoff. Under each dog, pressure (P), flow (Q), venous pressure (V) and resistance are tabulated.

In the final section, page C13, a comparison between constant pressure and constant flow measurement of resistance is made. For each dog where measurements are available the first three columns refer to constant pressure measurements - Const P, flow and Res, - and the final column shows the corresponding constant flow measurement of resistance.

Flow in each of these Tables is measured in ml/min, pressure in mmHg and resistance in mPRU.

DOG EXPERIMENT 2

SIDEARM RESISTANCE CALIBRATION

		Blood		Saline		Dextran	
DOG	Q	P	Res	P	Res	P	Res
11	45	20	444	12.5	277	25	555
	83	40	481	29	349	50	602
	117	60	512	50	427	80	683
	153	92	601	85	555	115	751
12	45	14	311	8	177	16.5	366
	83	24	289	15	180	30	361
	117	34	290	22.5	192	43	367
	153	48	313	35	228	62	405
13	45	20	444	18	400	23	511
	83	52	626	35	421	48	578
	117	83	709	52	444	73	629
	153	100	653	74	483	105	686
14	45	12	266	7.5	166	-	-
	83	25	301	16	192	-	-
	117	40	341	25	213	-	-
	153	58	379	37	241	-	-

Q Flow ml/min
P Pressure mmHg
Res Resistance mPRU

Table 1

DOG EXPERIMENT 2

PRESSURE MEASUREMENT - BLOOD

Conc	Side	Stab	Conc	Side	Stab
150	160	150	157	185	162
177	220	183	20	30	20
25	50	24	30	75	30
72	93	74	50	105	51
132	145	137	207	230	215
330	415	400	40	52	40
54	80	53	70	150	72
190	300	197	93	100	95
115	132	120	132	160	135
145	185	150	18	28	18
24	42	22	27	58	27
35	82	35	115	125	120
133	153	137	137	170	142
152	200	157	32	42	32
36	58	36	38	73	39
42	98	42	112	125	115
127	130	132	137	182	142
120	187	125	32	46	30
42	70	42	49	94	48
52	120	52	95	105	95
115	140	115	135	175	135
150	210	150	30	42	40
36	50	40	40	82	43
42	105	44	50	55	40
100	125	66	117	160	85
130	190	100	19	32	30
19	32	30	28	68	32
32	86	34	70	80	58
82	100	68	90	122	80
105	150	90	28	38	22
34	55	25	36	68	36
42	88	42			

Table 2

DOG EXPERIMENT 2

PRESSURE MEASUREMENT - SALINE

Conc	Side	Stab	Conc	Side	Stab
58	62	60	73	82	74
95	115	100	12	15	11
15	24	15	17	34	17
180	235	190	30	34	30
40	50	42	52	70	53
57	90	60	27	43	28
32	73	42	18	115	18
22	20	23	60	62	60
75	85	77	86	95	83
92	115	92	12	15	12
14	24	14	16	34	15
18	50	18	105	107	105
120	135	122	125	150	130
130	165	135	22	26	22
26	40	26	29	54	29
32	70	32	42	45	42
46	54	46	50	70	50
56	87	56	13	15	12
15	23	14	16	34	16
18	48	18	60	62	60
75	85	75	82	100	80
90	120	85	26	28	27
30	40	29	32	50	32
33	62	33	37	40	33
46	54	43	53	68	50
62	86	55	56	60	56
66	76	68	75	92	76
83	43	85	19	22	19
22	32	22	26	42	26
28	52	28			

Table 3

DOG EXPERIMENT 2

PRESSURE MEASUREMENT - DEXTRAN

Conc	Side	Stab	Conc	Side	Stab
117	127	120	175	195	180
195	230	205	20	28	18
22	42	22	27	62	26
132	160	137	165	200	170
192	285	200	38	62	40
47	100	48	56	145	58
64	175	66	212	325	225
150	160	155	205	285	215
207	240	215	20	28	18
30	50	30	40	75	40
52	102	52	70	75	72
140	165	145	140	175	143
152	205	157	35	47	35
42	68	42	50	90	50
54	110	54	82	95	85
100	125	102	117	130	120
127	182	132	20	30	18
30	52	30	46	82	45
54	107	54	42	52	40
50	75	50	34	45	34
62	120	60	34	45	34
46	69	45	54	94	52
58	117	57	115	125	120
125	140	130	150	175	155
165	220	170	20	28	20
25	43	24	54	86	55
58	100	58	72	82	73
84	105	86	96	130	98
110	155	115	28	38	28
35	55	35	40	74	42
45	92	46			

Table 4

DOG EXPERIMENT 2

BLOOD BY PUMP

Upper runoff - Pre ischaemia

	45ml/min			83ml/min			117ml/min			153ml/min		
Dog	P	V	Res	P	V	Res	P	V	Res	P	V	Res
11	150	1.0	3310	157	1.5	1875	177	1.5	1500	-		
12	93	1.0	2045	115	1.5	1365	132	1.5	1115	145	1.5	935
13	112	3.0	2420	127	3.0	1495	137	3.0	1145	120	4.2	755
14	50	0.0	1110	100	0.5	1200	117	0.5	995	130	0.6	845

Lower runoff - Pre ischaemia

11	20	1.0	420	25	1.5	285	30	2.0	240	-		
12	18	2.0	355	24	2.0	265	27	2.2	210	35	2.5	210
13	32	3.2	640	42	3.5	465	49	3.5	390	52	4.0	315
14	19	0.8	405	19	0.8	220	28	0.9	231	32	1.0	200

Upper runoff - Post ischaemia

11	132	4.0	2845	207	4.0	2445	330	4.2	2785	-		
12	115	4.0	2465	133	4.0	1555	137	4.5	1130	152	5.0	960
13	95	5.0	2000	115	5.0	1325	135	5.0	1110	150	5.5	975
14	70	1.8	1515	82	1.8	965	90	2.0	750	105	2.0	675

Lower runoff - Post ischaemia

11	27	5.0	490	32	5.0	325	18	4.5	115	-		
12	32	5.5	590	36	5.5	380	73	6.7	265	42	5.0	240
13	30	6.0	535	36	6.0	360	40	6.2	270	42	7.0	230
14	28	2.2	575	34	2.4	380	36	2.4	270	42	2.8	260

Table 5

DOG EXPERIMENT 2

SALINE BY PUMP

Upper runoff - Pre ischaemia

	45ml/min			83ml/min			117ml/min			153ml/min		
Dog	P	V	Res	P	V	Res	P	V	Res	P	V	Res
11	58	3.0	1220	73	3.5	835	95	4.0	775	-		
12	60	2.8	1270	75	3.0	930	86	3.0	710	92	3.2	580
13	42	4.0	845	46	4.5	500	50	4.5	390	56	4.5	335
14	37	1.0	800	46	1.0	540	53	1.2	440	62	1.2	395

Lower runoff - Pre ischaemia

11	12	3.2	195	15	3.5	140	17	4.5	105	-		
12	12	3.5	190	14	3.5	125	16	3.5	105	18	4.0	90
13	13	4.5	190	15	4.5	125	16	4.8	95	18	5.0	85
14	12	1.5	235	14	1.6	150	16	1.8	120	18	2.0	105

Upper runoff - Post ischaemia

11	40	4.5	790	52	4.5	450	-					
12	105	5.5	2220	120	6.0	1375	125	6.0	1015	130	6.5	805
13	60	7.0	1175	75	7.1	820	82	7.5	635	90	7.8	535
14	56	2.8	1135	66	3.0	760	75	3.2	615	83	3.3	520

Lower runoff - Post ischaemia

11	27	5.0	490	32	5.0	325	18	4.5	115	-		
12	22	6.8	335	40	7.0	230	29	7.0	190	32	7.5	155
13	26	8.0	400	30	8.0	265	32	8.2	205	33	9.0	155
14	19	3.4	345	22	3.5	220	26	3.6	190	28	3.8	160

Table 6

DOG EXPERIMENT 2

DEXTRAN BY PUMP

Upper runoff - Pre ischaemia

	45ml/min			83ml/min			117ml/min			153ml/min		
Dog	P	V	Res	P	V	Res	P	V	Res	P	V	Res
11	117	7.0	2445	175	7.5	2020	195	8.0	1600	-		
12	150	3.5	3255	205	3.5	2425	207	3.5	1740	-		
13	82	4.5	1720	100	4.5	1150	117	4.5	960	127	4.8	800
14	115	2.0	2510	125	2.0	1480	150	2.0	1265	165	2.0	1065

Lower runoff - Pre ischaemia

11	20	8.0	266	22	7.5	175	27	8.0	160	-		
12	20	4.5	305	30	4.5	305	40	4.7	300	52	5.0	305
13	20	4.8	335	30	5.0	300	46	5.0	350	54	5.5	315
14	20	2.0	400	25	2.0	275	54	2.0	445	58	2.0	366

Upper runoff - Post ischaemia

11	132	4.2	2840	165	3.5	1945	192	4.7	1600	-		
12	70	7.0	1400	140	7.2	1595	140	7.0	1135	152	8.5	935
13	42	8.5	745	50	8.6	500	34	10	205	62	9.4	345
14	72	3.5	1520	84	3.6	970	96	3.8	790	110	4.0	690

Lower runoff - Post ischaemia

11	38	4.7	740	47	4.5	510	56	4.0	445	-		
12	35	7.0	620	42	7.0	420	50	7.0	365	54	7.0	305
13	34	10	535	46	10	435	54	10	375	58	10	315
14	28	4.1	530	35	4.2	370	40	4.4	340	45	4.6	265

Table 7

DOG EXPERIMENT 2

MANUAL INFUSION BLOOD

Pre Ischaemia

	Upper runoff				Lower runoff			
Dog	P	Q	V	Res	P	Q	V	Res
11	100	21.4	5.5	4415	40	225	5.5	155
	125	41.8	6.5	2835	50	225	6.7	190
	150	100	6.0	1440	70	360	5.5	180
12	75	32.1	4.0	2210	42	257	4.0	147
	100	78.2	4.0	1225	50	189	9.5	243
	130	150	4.0	840	62	225	4.0	255
13	100	225	5.5	420	25	109.7	6.2	171
	125	260	5.8	460	48	473	6.0	90
	150	360	6.0	400	75	310	6.2	221
14	87	257	2.0	330	32	230	2.0	130
	120	409	2.0	290	47	500	2.0	90
	150	545	2.0	270	60	782	2.0	74

Post ischaemia

11	100	50	3.7	1925	78	83	3.0	905
	130	81.8	3.5	1545	90	150	2.5	585
	190	131	3.5	1425	115	281	2.5	400
12	100	45	7.0	2065	30	61.6	7.2	370
	130	104	6.8	1185	52	230	7.5	195
	170	187.5	7.0	870	62	339	7.2	160
13	100	68	9.5	1330	50	104	8.8	395
	125	107	9.5	1080	77	333	8.7	205
	150	183.6	8.0	775	90	450	8.5	180
14	100	115	4.0	835	50	200	4.0	230
	125	209	4.0	580	75	473	3.5	150
	150	290	3.8	505	85	666	3.7	120

Table 8

DOG EXPERIMENT 2

MANUAL INFUSION SALINE

Pre Ischaemia

	Upper runoff				Lower runoff			
Dog	P	Q	V	Res	P	Q	V	Res
11	75	54.8	6.0	1260	20	136	6.7	95
	90	69.2	6.0	1215	25	357	6.2	50
	112	160	7.0	655	30	542	6.5	45
12	100	56.2	4.0	1710	20	166	5.5	85
	120	121	4.5	955	25	225	5.5	86
	145	333	5.0	420	-			
13	100	187.5	7.0	495	17	580	8.5	15
	110	360	7.0	285	19	78.2	8.0	140
	150	562.5	7.2	255	24	321	8.0	49
14	75	225	2.0	325	20	150	2.0	120
	85	346	2.0	240	25	243	2.0	95
	125	500	2.0	245	75	720	2.0	100
Post ischaemia								
11	95	36.7	2.2	2530	37	315	2.0	110
	125	102	2.5	1200	50	72	2.5	660
	150	195	2.5	755	75	150	2.0	486
12	100	90	7.5	1025	52	257	8.0	170
	120	160	7.8	700	62	375	8.0	145
	155	236.8	8.2	620	75	169.8	8.0	395
13	100	145	9.2	625	30	56.2	10	355
	125	250	9.2	465	50	214	10	185
	150	418	9.5	335	55	720	10	60
14	100	125	4.0	770	30	132	4.5	195
	125	257	4.0	470	50	391	4.4	115
	150	375	4.2	115	-			

Table 9

DOG EXPERIMENT 2

MANUAL INFUSION DEXTRAN

Pre Ischaemia

	Upper runoff				Lower runoff			
Dog	P	Q	V	Res	P	Q	V	Res
11	100	30	6.0	3135	27	104.6	7.0	190
	125	62.5	6.5	1815	35	200	8.5	130
	150	200	6.7	591	40	122.4	7.5	265
12	110	30.8	5.5	3392	40	257	7.0	130
	155	112.5	6.0	1325	52	342	7.5	130
	200	276	6.5	700	62	176	7.2	310
13	130	121.6	9.0	995	25	70.3	7.5	250
	155	173	9.0	843	37	236	7.5	125
	185	300	9.0	585	40	236	9.5	129
14	90	95	2.0	925	25	75	2.0	305
	125	409	2.0	300	40	118	2.0	320
	160	418	2.0	375	50	253	2.0	190
Post ischaemia								
11	115	38	6.5	2895	75	53	7.0	1285
	160	81.8	7.0	1870	100	132	7.5	700
	190	126	7.0	1450	125	204	7.5	575
12	75	51.1	7.5	1320	75	51.1	7.5	1320
	155	81.8	7.0	1810	100	195	8.2	470
	200	150	7.0	1285	125	400	9.0	290
13	100	36.8	10	2445	85	281	11	265
	175	160	10	1030	100	375	11	235
	207	250	10	790	125	562	11.8	200
14	100	83	4.6	1150	52	140	5.3	335
	150	264	4.8	550	70	321	5.1	200
	200	418	4.8	465	95	692	5.0	130

Table 10

DOG EXPERIMENT 2

CONSTANT PRESSURE VS. CONSTANT FLOW

Dog No	Const P	Flow	Res	Res Const Q
11	125	41.8	2835	3310
12	100	78.2	1225	1365
	130	150	840	935
11	130	81.8	1545	2445
12	100	45	2065	2465
13	125	107	1080	1110
14	100	115	835	750
13	25	109.7	171	390
11	78	83	905	325
12	120	121	955	710
12	100	90	1025	1375
13	100	145	625	535
14	100	125	770	615
12	20	166	85	90
13	19	78.2	140	125
14	20	150	120	105
12	155	112.5	1325	1740
13	130	121.6	995	960
11	160	81.8	1870	1945
12	155	81.8	1810	1595
12	200	150	1285	935
13	175	160	1030	345
14	100	83	1150	970
14	25	75	305	370
14	40	116	320	340
14	52	140	325	265

Table 11

APPENDIX

Section D

In this section raw data from the femoropopliteal and femorotibial groups are listed. The first section, pages D3 - D5, contains the results of the comparison between concentric and sidearm measurement of resistance. For each infusion fluid, and at each flow rate, pressure by the two methods (Conc) and (Side) are listed with venous pressure (V), and resistance by the stab (Res 1) and sidearm (Res 2) methods. Measurements before and after Papaverine were available for both fluids.

In the second section, pages D6 - D13, is the raw data of pressure and resistance for both the groups. For each patient, collateral pressure (Coll), flow (Q), arterial pressure (P), venous pressure (V), and resistance (Res) are tabulated.

In the next section, pages D14 - D16, post papaverine results for the femoropopliteal group are are listed in the same way as for the previous section.

The final section, pages D17 - D18, contains the

raw data of resistance in the femoropopliteal group above and below knee. All measurements were taken prior to papaverine. In the first Table all above knee measurements of resistance were grouped together by flow rate. The second Table lists both below knee measurements of resistance for single vessel runoff and all cases together.

FEMOROPOPLITEAL GRAFTS CONCENTRIC AND SIDEARM

BLOOD - PRE PAPAVERINE

No	Flow	Conc Press	Side Press	V	Res 1 Conc	Res 2 Side	Res1/Res2
1	81	100	156	8	1135	1827	0.62
2	81	80	152	4	938	1827	0.513
	117	200	320	4	1675	2700	0.62
	153	260	432	4	1673	2797	0.598
3	81	44	104	6	469	1209	0.387
	117	52	152	6	393	1247	0.315
	153	61	200	6	359	1267	0.283
4	81	95	160	11	1037	1839	0.563
5	81	82	118	9	901	1345	0.699
6	81	47	82	9	469	901	0.52
7	81	60	112	12	592	1234	0.479
8	81	82	146	12	864	1654	0.52
9	45	72	86	10	1377	1688	0.815
	81	90	130	9	1000	1493	0.669
	117	98	172	9	760	1393	0.545
	153	104	216	9	620	1352	0.458
10	81	70	110	8	765	1259	0.607
	117	78	140	8	598	1128	0.53
	153	80	176	8	470	1098	0.428

Table 1

POST PAPAVERINE - BLOOD

No	Flow	Conc Press	Side Press	V	Res 1 Conc	Res 2 Side	Res1/Res2
1	81	58	112	8	617	1283	0.48
2	81	32	140	4	345	1679	0.205
	117	38	200	4	290	1675	0.173
	153	40	272	4	235	1751	0.134
3	81	28	92	4	296	1086	0.272
	117	34	136	4	256	1111	0.23
	153	34	176	4	196	1124	0.179
4	81	54	156	10	543	1802	0.301
5	81	46	84	10	444	913	0.486
	117	65	130	10	470	1025	0.458
6	81	43	80	9	419	876	0.478
7	81	46	96	12	419	1135	0.369
8	81	70	140	13	703	1567	0.448
9	81	56	96	12	543	1037	0.523
	117	64	134	11	470	1051	0.447
	153	68	180	12	366	1098	0.333
10	81	40	80	9	382	876	0.436
	117	45	110	9	307	863	0.355
	153	50	148	10	261	901	0.289

Table 2

FEMOROPOPLITEAL GRAFTS CONCENTRIC AND SIDEARM

SALINE - PRE PAPAVERINE

No	Flow	Conc Press	Side Press	V	Res 1 Conc	Res 2 Side	Res1/Res2
1	81	65	94	10	876	1037	0.844
	117	74	120	10	547	940	0.581
4	81	30	84	8	271	938	0.288
5	81	40	70	10	370	740	0.5
6	81	30	47	9	259	469	0.552
7	81	44	72	13	382	728	0.53
8	81	65	108	12	654	1185	0.551

POST PAPAVERINE

No	Flow	Conc Press	Side Press	V	Res 1 Conc	Res 2 Side	Res1/Res2
1	81	44	69	10	419	728	0.575
	117	44	88	10	290	666	0.435
5	81	25	62	10	185	641	0.288
8	81	60	106	12	592	1160	0.51

Table 3

FEMOROTIBIAL GRAFTS

Name	Coll	Q	P	V	Res
1	12	9.5	28	10	1894
		45	51	10	911
		81	62	10	641
		117	64	10	461
		153	64	10	352
2	24	9.5	68	15	5778
		19.1	-	-	-
		38.2	134	15	3120
		76.4	166	14	1990
3	38	19.1	116	10	5555
		38.2	154	10	3760
		76.4	188	6	2380
4	35	9.5	45	14	3263
		19.1	57.4	14	2260
		38.2	80	14	1727
		76.4	140	14	1650
5	24	9.5	41	10	3263
		19.1	75	8	3507
		38.2	120	9	2905
		76.4	208	8	2610
6	30	9.5	43	4	4105
		19.1	70	4	3455
		38.2	112	3	2853
		76.4	192	2	2486
		190	360	2	1884
7	52	19.1	182	5	9267
		38.2	220	5	5628
		76.4	280	5	3599

Table 4

Cont...

PERIPHERAL RESISTANCE MEASUREMENT App.D

Name	Coll	Q	P	V	Res
8	53	19.1	96	8	4607
		38.2	140	8	3455
		76.4	240	8	3036
9	33	9.5	59	8	5368
		19.1	92	8	4397
		38.2	96	7	2329
		76.4	122	6	1518
		190	126	6	631
10	22	19.1	240	6	12251
		38.2	400	6	10314
11	44	19.1	63	8	2879
		38.2	78	8	1832
		76.4	100	8	1204
		153	128	8	784
12	11	19.1	75	6	3612
		38.2	110	6	2722
		76.4	140	6	1753
		153	190	6	1202
13	42	19.1	140	10	6806
		38.2	200	10	4973
		76.4	268	10	3376
		153	344	10	2183
14	20	117	100	15	726
15		-	-	-	-
16	30	9.5	32	16	1684
		45	50	15	777
		81	80	16	790
		117	90	17	623
		153	128	15	738
17	20	9.5	36	12	2526
		45	62	12	1111
		81	89	12	950
		117	114	12	871
		153	134	13	790

Table 4

Cont...

Name	Coll	Q	Q	V	Res
18	25	9.5	38	11	2842
		45	72	10	1377
		81	92	10	1012
		117	112	11.5	858
		153	122	10	732
19	24	45	46	6	888
		81	62	6	691
		117	81	6	641
		153	100	6	614
20	24	81	81	4	950
		117	100	4	820

Table 4

FEMOROPOPLITEAL GRAFTS

Name	Coll	Q	P	V	Res
1	20	19.1	67	2.5	3360
		38.2	50	2.0	1250
		76.4	95	2.5	1210
2	30	9.5	31	10	2210
		19.1	35	10	1315
		38.2	45	10	921
		76.4	52	10	552
		190	77	10	352
3	30	19.1	70	11	3100
		38.2	88	11	2020
		76.4	116	11	1380
		152	140	11	843
4	52	19.1	52	12.5	2080
		38.2	56	12.5	1140
		76.4	70	12.5	888
		152	93	12.5	530
5	20	19.1	32	4	1460
		38.2	39	4	916
		76.4	43	4	511
		152	48	4	289
6	18	19.1	-	-	-
		38.2	-	-	-
		76.4	-	-	-
		152	-	-	-
7	16	19.1	30	8	1150
		38.2	37	8	759
		76.4	55	8	615
		152	98	8	592

TABLE 5

Cont...

No	Coll	Q	P	V	Res
8	12	19.1	32	3	1510
		38.2	40	3	968
		76.4	54	3	667
		152	77	3	486
9	18	19.1	84	20	3340
		38.2	122	22	2610
		76.4	192	21	2240
		152	292	21	1780
10	55	19.1	84	9	3910
		38.2	100	9	2380
		76.4	124	9	1500
		152	160	10	987
11	24	19.1	97	19	4105
		38.2	138	19	3130
		76.4	260	19	1575
12	40	45	62	18	977
		81	78	18	740
		117	93	18	641
		153	102	18	549
13	40	45	53	6	1040
		69	70	6	925
		96	86	7	830
		124	98	7	740
14	17	45	-	-	-
		83	-	-	-
		117	-	-	-
15	50	45	77	16	1350
		81	70	16	666
		117	77	16	520
16	80	45	96	16	1777
		81	104	16	1086
		117	104	15	760
		153	116	15	660

TABLE 5

Cont...

No	Coll	Q	P	V	Res
17	10	45	38	6	711
		81	44	6	469
		117	49	6	367
		153	52	6	300
18	62	45	85	16.5	1522
		81	96	16.5	981
		117	102	16.5	730
		153	102	16.5	558
19	46	45	64	8	1244
		81	82	8	913
		117	84	8	663
		153	-	-	-
20	38	45	78	7	1577
		81	100	7	1148
		117	116	7	931
		153	116	7	712
21	36	45	42	6	800
		81	57	10	580
		117	64	10	461
		153	68	10	379
22L(a)	18	19.1	42	3	2050
		38.2	46	3	1130
		76.4	50	3	618
		152	63	3	392
22R(b)	14	45	40	8	711
		81	54	8	567
		117	60	7	452
		153	-	-	-
23	40	45	52	6	1022
		81	65	6	728
		117	66	6	512
		153	68	6	405
24	22	45	45	6	866
		81	58	6	641
		117	64	6	495
		153	65	6	385

TABLE 5

Cont...

No	Coll	Q	P	V	Res
25	20	45	38	5	733
		81	45	5	493
		117	47	5	358
		153	50	5	294
26	64	45	82	6	1688
		81	104	6	1209
		117	118	6	957
		153	130	6	810
27	32	45	60	8	1155
		81	85	8	950
		117	95	8	743
		153	90	6	549
28	32	45	90	8	1822
		81	110	8	1259
		117	128	8	1025
		153	144	7	895
29	70	45	136	8	2844
		81	180	8	2123
		117	200	8	1641
		153	248	8	1568
30	50	45	98	6	2044
		81	122	6	1432
		117	140	6	1145
		153	154	6	967
31R(a)	74	45	98	12	1911
		81	118	13	1296
		117	132	14	893
		153	130	11	777
31L(b)	20	81	82	9	901
32	38	45	62	8	1200
		81	82	8	913
		117	84	8	649
		153	82	8	483

TABLE 5

Cont...

PERIPHERAL RESISTANCE MEASUREMENT App.D

No	Coll	Q	P	V	Res
33L(a)	62	45	78	6	1600
		81	86	6	987
		117	94	6	752
		153	100	6	614
33R(b)	55	45	62	8	1200
		81	70	8	765
		117	78	8	598
		153	80	8	470
34	56	45	72	10	1377
		81	90	9	1000
		117	98	9	760
		153	104	9	620
35	24	45	126	5	2688
		81	160	5	1913
		117	192	5	1598
		153	200	5	1274
36	22	45	40	6	755
		81	44	6	469
		117	52	6	393
		153	61	6	359
37	58	81	86	8	962
38L(a)	31	45	70	9	1355
		81	96	9	1074
		117	124	9	982
		153	-	-	-
38R(b)	44	81	72	7	802
39	39	81	95	11	1037
40	48	81	60	12	592

TABLE 5

FEMOROPOPLITEAL GRAFTS - POST PAPAVERINE

Name	Q	P	V	Res
7	19.1	29	9	1047
	76.4	64	9	719
8	76.4	47	4	562
9	38.2	82	23	1544
	76.4	120	24	1256
	153	196	24	1124
10	38.2	80	9	1858
	76.4	68	10	759
	153	98	10	575
11	76.4	110	20	1178
12	45	42	18	533
	81	62	16	567
13	-	-	-	-
14	81	-	-	-
	117	-	-	-
	153	-	-	-
15	81	63	16	580
	117	70	16	461
16	117	64	19	384
17	117	48	7	350
18	81	50	18	395
	117	50	18	273
	153	50	18	209
19	117	36	9	230

Table 6

Cont...

Name	Q	P	V	Res
20	45	40	7	733
	81	44	7	456
	117	42	7	299
21	81	56	6	617
	117	71	6	555
	153	85	7	509
22b	81	40	8	395
	117	48	8	341
23	81	38	8	370
	117	36	8	239
	153	28	8	130
24	81	26	4	271
	117	28	4	205
25	81	24	4	246
	117	24	4	170
	153	40	4	235
26	81	60	6	666
	117	64	6	495
	153	87	6	529
27	81	30	8	271
	117	30	8	188
28	81	50	8	518
	117	56	8	410
	153	76	8	444
29	81	164	8	1925
	117	220	8	1811
	153	240	9	1509

Table 6

Cont...

Name		Q	P	V Res
31a	81	48	6	518
	117	70	6	547
	153	70	6	418
31b	81	46	10	444
	117	65	10	470
32	81	26	10	197
	117	28	10	153
	153	30	10	130
33a	81	46	6	493
	117	40	6	290
	153	40	6	222
33b	81	40	9	382
	117	45	9	307
	153	50	10	261
34	81	56	12	543
	117	64	11	470
	153	68	12	366
36	81	28	4	296
	117	34	4	256
	153	34	4	196
37	81	64	8	691
38a	81	50	7	530
38b	81	100	10	1111
39	81	54	10	543
40	81	46	12	419
	117	54	12	358

Table 6

FEMOROPOPLITEAL GROUP - RESISTANCE ABOVE KNEE

PRE PAPAVERINE

Flow	45	81	117	153 ml/min
Res	1140	888	512	530
	1086	760	358	660
	1130	618	957	392
	1022	728	743	405
	733	493	649	294
	1688	1209	752	810
	1155	950	598	549
	1200	913		483
	1600	987		614
	1200	765		470
Mean	1195	831	652	520
SE	91	67	77	49
N	10	10	7	10

Table 7

FEMOROPOPLITEAL GROUP - RESISTANCE BELOW KNEE

PRE PAPAVERINE

Vessels	45 ml/min		81 ml/min		117 ml/min		153 ml/min	
	One	All	One	All	One	All	One	All
	1250	916	1210	511	663	520	843	289
	921	2380	552	1500	931	367	486	987
	2020	1040	1380	666	1145	730	1780	300
	968	1350	667	469	760	495	712	558
	2610	711	2240	981	1598	641	967	385
	3130	1522	1575	641	393	461	620	592
	1244	866	913	615	982	452	1274	549
	1577	759	1148	740		1025	359	379
	2044	977	1432	580		893		895
	1377	800	901	567		752		777
	2688	711	1000	1259		663		614
	755	1822	1913	1296		931		843
	1355	1911	469	987		1145		486
		1600	1074	962		760		1780
		1250	802	1037		1598		712
		921		592		393		967
		2020		1210		982		620
		968		552				1274
		2610		1380				359
		3130		667				
		1244		2240				
		1577		1575				
		2044		913				
		1377		1148				
		2688		1432				
		755		901				
		1355		1000				
				1913				
				469				
				1074				
				802				
Mean	1687	1455	1151	989	924	753	880	703
SE	216	131	131	79	156	80	174	87
N	13	27	15	31	7	17	8	19

Table 8

REFERENCES

Agerskov K, Faris I, Tonnesen KH, Kristensen P, Christensen SC.
Popliteal artery puncture in the assessment of patients with severe leg ischaemia.
Ann Surg. 1983; 198: 771-775.

Angelides NS, Nicolaides AN.
Simultaneous isotope clearance from the muscles of the calf and thigh.
Br J Surg. 1980; 67: 220-224.

Archie JP, Feldtman W.
Determination of the haemodynamic significance of iliac artery stenosis by non-invasive Doppler ultrasonography.
Surgery. 1982; 91: 419-424.

Auerbach O, Hammond EC, Garfinkel L.
Smoking in relation to atherosclerosis of the coronary arteries.
N. Eng J. Med. 1965; 273: 775-779.

Baddeley RM, Ashton F, Slaney GG, Barnes AD.
Late results of autogenous vein bypass grafts in femoropopliteal arterial occlusion.
Br Med J. 1970; 653-656.

Barner HB, Kaminski DL, Codd JE, Kaiser GC, Willman VL.
Hemodynamics of autogenous femoropopliteal bypass.
Arch Surg. 1974; 109: 291-293.

Baumgartner HR.
The subendothelial surface and thrombosis.
Thrombosis et Diathesis Haemorrhagica. 1974; 59(suppl): 91.

Beard JD, Fairgrieve J.
Compliance changes in in-situ femoropopliteal bypass vein grafts.
Br J Surg. 1986; 73: 196-199.

Benditt EP.
The origin of atherosclerosis.
Scientific American. 1977; 236: 74-85.

Bell PRF, Charlesworth D, DePalma RG, Eastcott HHG, Eklof B, Gruss JD, Jamieson CW, Morris PJ, Nicolaides AN, Rutherford RB.
The definition of critical ischaemia of a limb.
Br J Surg. 1982; 69(suppl): 2.

Bell PRF.
Are distal vascular procedures worthwhile?
Br J Surg. 1985; 72: 335.

Bergan JJ, Yao JST, Flinn WR, Graham LM.
Prosthetic grafts for the treatment of lower limb ischaemia; present status.
Br J Surg. 1982; 69: S34-37.

Bernhard VM, Ashmore CS, Evans WE, Rodgers RE.
Bypass grafting to distal arteries for limb salvage.
Surg Gynaecol Obstet. 1972; 135: 219-224.

Bliss BP.
Peripheral resistance in the leg in arterial occlusive disease.
Cardiovasc Res. 1971; 5: 337-342.

Bliss BP.
Pressure flow and peripheral resistance measurements during surgery for femoropopliteal occlusion (Preliminary observations on 21 limbs.
Scand J Clin Lab Invest. 1973; 31 (suppl 128): 179-183.

Boobis LH, Bell PRF.
Can drugs help patients with lower limb ischaemia?
Br J Surg. 1982; 69(suppl): 17-23.

Brandman O, Redisch W.
Incidence of peripheral vascular changes in diabetes mellitus.
Diabetes. 1953; 2: 194-198.

Campbell WB, Cole SEA, Skidmore R, Baird RN.
The clinician and the vascular laboratory in the diagnosis of aortoiliac stenosis.
Br J Surg. 1984; 71: 302-306.

Cappelen CJ, Hall KV.
Electromagnetic flowmetry in clinical surgery.
Acta Chir Scand. 1967; suppl 368: 2-27.

Cave FD, Walker A, Naylor GP, Charlesworth D.
The hydraulic impedance of the lower limbs - its relevance to the success of bypass operations for occlusion of the superficial femoral artery.
Br J Surg. 1976; 63: 408-412.

Charlesworth D, Harris PL, Cave FD, Taylor L.
Undetected aorto-iliac insufficiency; a reason for early failure of saphenous vein bypass grafts for obstruction of the superficial femoral artery.
Br J Surg. 1975; 62: 567-570.

Charlesworth D, Brewster DC, Darling RC, Robinson JG, Hallet JW,
The fate of polytetrafluoroethylene grafts in lower limb surgery; a six year follow-up.
Br J Surg. 1985; 72: 896-899.

Chamberlain J, Housley E, Macpherson AIS.
The relationship between ultrasound assessment and angiography in occlusive arterial disease of the lower limb.
Br J Surg. 1975; 62: 64-67.

Conrad MC, Green HD.
Hemodynamics of large and small vessels in peripheral vascular disease.
Circulation. 1964; 29: 847-853.

Cranley JJ, Hafner CD.
Newer prosthetic material compared with autogenous vein for occlusive arterial disease of the lower extremity.
Surgery. 1981; 89: 1-7.

Crawford ES, De Bakey ME, Baisdell FW, Morris G, Fields WF.
Hemodynamic alterations in patients with cerebral arterial insufficiency before and after operation.
Surgery. 1960; 48: 76-94.

Cutler BS, Thompson JE, Kleinsasser LJ, Hempel GK.
Autologous saphenous vein femoropopliteal bypass; Analysis of 298 cases.
Surgery. 1976; 79: 325-331.

Dardik H, Dardik II, Sprayregen S, Ibrahim IM, Veith F.
Small vessel reconstructive surgery of the lower extremities.
Angiology. 1975; 26: 683-688.

Dardik H, Ibrahim IM, Dardik II.
The role of the peroneal artery for limb salvage.
Ann Surg. 1979; 189: 189- 198.

Dardik H, Ibrahim IM, Sussman B, Greweldinger J, Adler J, Kahn M, Dardik I.
Morphologic structure of the pedal arch and its relationship to patency of crural vascular reconstruction.
Surg Gynaecol Obstet. 1981; 152: 645-648.

Dedichen H.
Prognostic significance of intra-operative flow and pressure measurements in reconstructive vascular surgery.
Scand J Clin Lab Invest. 1973; 31(suppl 128): 189-192.

Dedichen H.
Measurement of arterial blood flow during surgery.
Acta Chir Scand. 1974; 140: 363-369.

Dedichen H, Myhre HO.
Reactive hyperaemia of the human lower limb.
Acta Chir Scand. 1975; 141: 517-521.

Dedichen H.
Hemodynamics in arterial reconstructions of the lower limb.
Acta Chir Scand. 1976; 142: 213-220.

Dedichen H.
Hemodynamics in arterial reconstructions of the lower limb.
Acta Chir Scand. 1976; 142: 221-225.

Delin A, Ekestrom S.
Evaluation of reconstructive surgery for arterial stenoses from intraoperative determinations of flow pressure and resistance.
Acta Chir Scand. 1965; 130: 35-41.

Demorais D, Johnston KW.
Assessment of aortoiliac disease by non-invasive quantitative Doppler waveform analysis.
Br J Surg. 1981; 68: 789-792.

Denison C, Hall KV.
A square-wave electromagnetic flowmeter for application to intact blood vessels.
Circ Res. 1955; 3: 39-46.

Denton MJ, Hill D, Fairgrieve J.
In situ femoropopliteal and distal vein bypass for limb salvage - experience of fifty cases.
Br J Surg. 1983; 70: 358-381.

Deweese JA, Rob CG.
Autogenous venous grafts ten years later.
Surgery. 1977; 82: 775-784.

DHSS and OPCS
Hospital inpatient enquiry, main tables.
1983; Series MB4 No 23.

Edmonds ME, Wilton GN, Roberts VC, Watkins PJ.
Blood flow in the diabetic neuropathic leg.
Diabetologia. 1980; 19: 272. (Abst)

Edwards EA, Cohen NR, Marshall MK.
Effect of exercise on peripheral pulses.
New Eng J Med. 1959; 260: 738-741.

Edwards WH, Wright RS.
Tibial and peroneal bypass in severe occlusive disease of the lower extremities.
Ann Surg. 1976; 183: 710-718.

Evans DH, Quin RO, Bell PRF.
The significance of blood pressure measurements in patients with peripheral vascular disease.
Br J Surg. 1980; 67: 238-241.

Evans DH, Macpherson DS, Bentley S, Asher MJ, Bell PRF.
The effect of proximal stenosis on Doppler waveforms. A comparison of three methods of waveform analysis in an animal model.
Clin Phys Physiol Meas. 1981; 2: 17-25.

Farrar DJ, Malindzak GS, Johnson G.
Dynamic pressure-flow diagrams and impedance in experimental arterial stenosis and in stenotic atherosclerosis.
Ann Biomed Eng. 1978; 6: 413-428.

Feins RH, Roedersheimer R, Baumstark AE, Green RM.
Predicted hyperaemic angiography; A technique of distal arteriography in the severely ischaemic leg.
Surgery. 1981; 89: 202-205.

Folse R. (a)
Alterations in femoral blood flow and resistance during rhythmic exercise and sustained muscular contractions in patients with arteriosclerosis.
Surg Gynecol Obstet. 1965; 120: 767-776.

Folse R. (b)
Application of the sudden injection dye dilution principle to the study of the femoral circulation.
Surg Gynecol Obstet. 1965; 120 1194-1206.

French JE.
Atherogenesis and thrombosis.
Seminars in Haematology. 1971; 8: 84-94.

Garrett WV, Slaymaker EE, Heintz SE, Barnes RW.
Intraoperative prediction of symptomatic result of aortofemoral bypass from changes in ankle pressure index.
Surgery. 1977; 82: 504-509.

Gill RW.
Measurement of blood flow by ultrasound; Accuracy and sources of error.
Ultrasound in Med and Biol. 1985; 11: 625-641.

Golding AL, Cannon JA.
Application of electromagnetic flowmeter during arterial reconstruction.
Ann Surg. 1966; 164: 662-675.

Goldman M, Hall C, Dykes J, Hawker RJ, McCollum CN.
Does indium-platelet deposition predict patency in prosthetic arterial grafts?
Br J Surg. 1983; 70: 635-638.

Green HD, Lewis RN, Nickerson ND, Heller AL.
Blood flow, peripheral resistance and vascular tonus, with observations on the relationship between blood flow and cutaneous temperature.
Am J Physiol. 1944; 141: 518-536.

Hall KV.
The great saphenous vein used in-situ as an arterial shunt after extirpation of vein valves.
Surgery. 1962; 51: 492-495.

Harris PL, Campbell H.
Adjuvant distal arteriovenous shunt with femorotibial bypass for limb salvage.
Br J Surg. 1983; 70: 377-380.

Hanson KM, Johnson PC.
Vascular resistance and arterial pressure in autoperfused dog hindlimb.
Am J Physiol. 1962; 203: 615-620.

Heintz SE, Bone GE, Slaymaker EE, Hayes AC, Barnes RW.
Value of arterial pressure measurements in the proximal and distal part of the thigh in arterial occlusive disease.
Surg Gynaecol Obstet. 1978; 146: 337-343.

Hughson WG, Mann JI, Garrod A.
Intermittent claudication; prevalence and risk factors.
Br Med J. 1978a; 1: 1379-1381.

Hughson WG, Mann JI, Tibbs DJ, Woods HF, Walton I.
Intermittent claudication; Factors determining outcome.
Br Med J. 1978b; 1: 1377-1379.

Hurlow RA, Chandler ST, Hardman J, Strachan CJL.
The non-invasive assessment of aortoiliac disease; A comparison of dynamic isotope angiology with thigh/brachial pressure index.
Surgery. 1978; 84: 278-282.

Ibrahim IM, Sussman B, Dardik I, Kahn M, Israel M, Kenney M, Dardik H.
Adjunctive arteriovenous fistula with tibial and peroneal reconstruction for limb salvage.
Am J Surg. 1980; 140: 246-251.

Imparato AM, Kim GE, Madayag M, Haveson SP.
The results of tibial artery reconstruction procedures.
Surg Gynaecol Obstet. 1974; 138: 33-38.

James PB, Galloway RW.
The ultrasonic blood velocity detector as an aid to arteriography.
Br J Rad. 1971; 44: 743-746.

Johansen K, Bernstein EF.
Revascularisation of the ischaemic canine hindlimb by arteriovenous reversal.
Ann Surg. 1979; 190: 243-255.

John HT, Warren R.
The stimulus to collateral circulation.
Surgery. 1961; 49: 14-25.

Juergens JL, Barker NW, Hines EA.
Arteriosclerosis obliterans - review of 520 cases with special reference to pathological factors and prognosis
Circulation. 1960; 21: 188-195.

Kahn PC, Boyer DN, Moran JM, Callow AD.
Reactive hyperaemia in lower extremity arteriography; An evaluation.
Radiology. 1968; 90: 975-980.

Kannel WB, Shurtleff D.
Cigarettes and the development of intermittent claudication.
Geriatrics. 1973; 28: 61-68.

Kannel WB, Wolf PA, Verter J, McNamara PM.
Epidemiologic assessment of the role of blood pressure in stroke. The Framingham Study.
JAMA. 1970; 214: 301-310.

Kao VCY, Wissler RW, Dzoga K.
The influence of hyperlipidaemic serum on the growth of medial smooth muscle cells of the rhesus monkey aorta in vitro.
Circulation. 1968; 6(suppl): 12.

Kirkendall WM, Burton AC, Epstein FH, Freis ED.
Recommendations for human blood pressure determination by sphygmomanometer.
Circulation. 1967; 36: 980-988.

Klimach O, Underwood CJ, Charlesworth D.
Femoropopliteal bypass with a Goretex prosthesis; a long-term follow-up.
Br J Surg. 1984; 71: 821-824.

Kolin A.
An electromagnetic flowmeter. Principle of the method and its application to bloodflow measurements.
Proc Soc Exper Biol and Med. 1936; 35: 53-56.

Koontz TJ, Stansel HC.
Factors influencing patency of the autogenous vein femoropopliteal graft; An analysis of 74 cases.
Surgery. 1972; 71: 753-759.

Kramann B.
Transvenous xeroarteriography; Non-invasive method for demonstrating peripheral arteries.
Am J Rad. 1979; 133: 245-250.

Kretschmer G, Wenzl E, Wagner O, Polterauer P, Ehringer H, Minar E, Schemper M.
Influence of anticoagulant treatment in preventing graft occlusion following saphenous vein bypass for femoropopliteal occlusive disease.
Br J Surg. 1986; 73: 689-692.

Law YF, Graham JC, Cotton LT, Roberts VC.
Per-operative haemodynamic assessment of lower limb arterial surgery. Part 1; Hydraulic impedance measurement.
J Biomed Eng. 1983; 5: 185-193.

Layer GT, King RB, Jamieson CW.
Early aneurysmal degeneration of human umbilical vein bypass grafts.
Br J Surg. 1984; 71: 709-710.

Lewis JD.
The role of measurement in peripheral vascular surgery.
Proc R Soc Med. 1974; 67: 443-444.

Lewis P, Psaila JV, Davies WT, McCarty K, Woodcock JP.
Measurement of volume flow in the human common femoral artery using a duplex ultrasound system.
Ultrasound in Med and Biol. 1986; 10: 777-784.

Linhart J, Dejdar R, Hlavova A, Kruszewska E.
Measurement of maximal calf flow in occlusive arterial disease of lower extremities.
Angiology. 1974; 25: 526-535.

Little JM, Shiel AGR, Loewenthal J, Goodman AH.
Prognostic value of intraoperative blood flow measurements in femoropopliteal bypass vein-grafts.
Lancet. 1968; 648-651.

Lorentsen E, Hoel BL, Hol R.
Evaluation of the functional importance of atherosclerotic obliterations in the aortoiliac artery by pressure/flow measurements.
Acta Med Scand. 1972; 191: 399-403.

Macpherson DS, Evans DH, Bell PRF.
Common Femoral artery Doppler wave-forms; a comparison of three methods of objective analysis with direct pressure measurements.
Br J Surg. 1984; 71: 46-49.

Malone JM, Moore WS, Goldstone J.
The natural history of bilateral aortofemoral bypass grafts for ischaemia of the lower extremities.
Arch Surg. 1975; 110: 1300-1306.

Mannick JA, Jackson BT, Coffman JD.
Hemodynamics of arterial surgery in atherosclerotic limbs. II. Comparison of intraoperative arterial pressure and flow with pre- and postoperative exercise blood flow.
Surgery. 1966; 60: 578-584.

Mason R, Lanfranchi A, Giron F.
Isolated popliteal versus distal bypasses for limb salvage.
Surg Gynaecol Obstet. 1982; 155: 49-52.

Mathieson FR, Larsen EE, Wulff M.
Some factors influencing the spontaneous course of arterial vascular insufficiency.
Acta Chir Scand. 1970; 43: 352-364.

McDonald DA.
From Blood flow in arteries. Edward Arnold Ltd, London. 1974.

Menzoian JO, La Morte WW Cantelmo NL, Doyle J, Sidawy AN, Savenor A.
The preoperative angiogram as a predictor of peripheral vascular runoff.
Am J Surg. 1985; 150: 346-352.

Mundth ED, Darling RC, Moran JM, Buckley MJ, Linton RR, Austen WG.
Quantitative correlation of distal arterial outflow and patency of femoropopliteal reversed vein grafts with intraoperative flow and pressure measurements.
Surg. 1969; 65: 197-206.

Myers KA, King RB, Scott DF, Johnson N, Morris PJ.
The effect of smoking on the late patency of of arterial reconstructions in the legs.
Br J Surg. 1978; 65: 267-271.

Myhre HO.
By-pass grafting for femoropopliteal atherosclerosis.
Acta Chir Scand. 1977 143: 109-113.

Naji A, Chu J, Mccombs PR, Barker CF, Berkowitz HD, and Roberts B.
Results of 100 consecutive femoropopliteal vein grafts for limb salvage.
Ann Surg. 1978; 188: 162-165.

Nicholas GG, Barker CF, Berkowitz HD, Roberts B.
Reconstructive surgery distal to the popliteal trifurcation.
Arch Surg. 1973; 107: 652-656.

Nicolaides AN.
Value of non-invasive tests in the investigation of lower limb ischaemia.
Ann R Coll Surg Engl. 1978; 60: 249-252.

Nielsen PE, Bell G, Lassen NA.
Strain gauge studies of distal blood pressure in normal subjects and in patients with peripheral arterial disease. analysis of normal variation and reproducibility and comparison to intraarterial measurements.
Scand L Clin Lab Invest. 1973 suppl 128; 31: 103-109.

OPCS.
Mortality Statistics: cause
1983; Series DH2 No 10.

O'Rourke MF, Taylor MG.
Vascular impedance of the femoral bed.
Circ Res. 1966; 18: 126-139.

Pappenheimer JR, Maes JP.
A quantitative measure of the vasomotor tone in the hindlimb muscles of the dog.
Am J Physiol. 1942; 137: 187-199.

Pappenheimer JR, Soto-Rivera A.
Effective osmotic pressure of the plasma proteins and other quantities associated with the capillary circulation in the hindlimb of cats and dogs.
Am J Physiol. 1948; 152: 471-491.

Poiseuille JLM.
Ann de Chim et de Physiol. 1843; 7: 50.

Quick CRG, Cotton LT.
The measured effect of stopping smoking on intermittent claudication.
Br J Surg. 1982; 69 (suppl): S24-26.

Quin RO, Evans DH, Bell PRF.
Haemodynamic assessment of aorto-iliac segment.
J Cardiovasc Surg. 1975; 16: 586-589.

Reichle FA, Rankin KP, Tyson R, Finestone AJ, Shuman C.
Long-term results of 474 arterial reconstructions for severely ischaemic limbs; A fourteen year follow-up.
Surgery. 1979; 85: 93-100.

Roberts VC, Cotton LT.
Electromagnetic blood flow measurement during extended deep femoral angioplasty.
Acta Chir Scand. 1977; 143: 413-416.

Roedersheimer LR, Feins R, Green RM.
Doppler evaluation of the pedal arch.
Am J Surg. 1981; 142: 601-604.

Sako Y.
Papaverine test in peripheral arterial disease.
Surgical Forum. 1966; 17: 141-143.

Scarpello JHB, Martin TRP, Ward JD.
Ultrasound measurements of pulse-wave velocity in the peripheral arteries of diabetic subjects.
Clin Sci. 1980; 58: 53-57.

Scheinin TM, Inberg MV.
Determination of blood flow in arterial surgery.
Acta Chir Scand. 1968; 134: 55-61.

Schenk WG, Menno AD, Anderson MN, Drapanas T.
Application of the electromagnetic flowmeter to vascular studies in human patients.
Surgery. 1960; 48: 211-218.

Serise JM, Le Heron D, Janvier G, Winnock S, Adoue B, Tingaud M, Bensouda M.
Mesure per-operative des resistances vasculaires peripheriques dans les pontages femoro-distaux.
J Mal Vasc. 1982; 7:325-327.

Sethia KK, Berry AR, Morrison JD, Collin J, Murie JA, Morris PJ.
Changing pattern of lower limb amputation for vascular disease.
Br J Surg. 1986; 73: 701-703.

Shearman CP, Gwynn BR, Curran F, Gannon MX, Simms MH.
Non-invasive femoropopliteal assessment; is that angiogram really necessary?
Br Med J. 1986; 293: 1086-1089.

Sonnenfeld T, Cronestrand R, Nowak J.
Leg haemodynamics during reconstructive vascular surgery.
Br J Surg. 1979; 66: 586-589.

Sonnenfeld T, Cronestrand R.
Intra-operative graft blood flow related to failure of femoro-popliteal bypass grafts.
Scand J Thor Cardiovasc Surg. 1980; 14: 101-104.

Sonnenfeld T, Cronestrand R, Von Euler C, Nowak J, Astrom H.
Leg haemodynamics during different forms of anaesthesia in patients undergoing reconstructive vascular surgery.
Acta Chir Scand. 1981; 147: 249-253.

Soulen RL, Tyson R, Reichle FA, Cohen AM.
Angiographic criteria for small vessel bypass.
Radiology. 1973; 107: 513-519.

Strandness DE Jr, Priest RE, Gibbonds GE.
Combined clinical and pathological study of diabetic and non-diabetic peripheral arterial disease.
Diabetes. 1964; 13: 366-372.

Szilagyi DE, Hageman JH, Smith RF, Elliot JP, Brown F, Deitz P.
Autogenous vein grafting in femoral atherosclerosis; The limits of its effectiveness.
Surgery. 1979; 86:: 836-851.

Terry HJ, Allan JS, Taylor GW.
The relationship between blood-flow and failure of femoropopliteal reconstructive arterial surgery.
Br J Surg. 1972; 59: 549-551.

Vanttinen E.
Electromagnetic measurement of the arterial blood flow in the femoropopliteal region.
Acta Chir Scand. 1975; 141: 353-359.

Veith FJ, Gupta SK, Samson RH, Scher LA, Fell SC, Weiss P, Janko G, Flores SW, Rifkin H, Bernstein G, Haimovici H, Gliedman ML, Sprayregen S.
Progress in limb salvage by reconstructive arterial surgery combined with new or improved adjunctive procedures.
Ann Surg. 1981; 194: 386-400.

Vetto RM, Dunphy JE.
Recent revisions in the operative treatment of vascular disease.
Surg Gynecol Obstet. 1964; 119: 1026-1030.

Ward JD.
The diabetic leg.
Diabetologia. 1982; 22: 141-147.

Watkins PJ.
Diabetic neuropathy.
Br. Med J. 1982; 285: 493-495.

Weale FE, Taylor GW, Rothwell-Jackson RL. (a)
The measurement of regional vascular resistance at operation.
Br J Surg. 1964; 51: 627-629.

Weale FE. (b)
The values of series and parallel resistances in steady blood-flow.
Br J Surg. 1964; 51: 623-627.

Weismann RE, Upson JF.
Intra-arterial pressure studies in patients with arterial insufficiency of the lower extremities.
Ann Surg. 1963; 157: 501-506.

Wetterer E.
Eine neue methode zur registrierung der blutstromungs-geschwindigkeit am uneroffneten gefass.
Ztschr f Biol. 1937; 98: 26-36.

Whitney RJ.
The measurement of volume changes in human limbs.
J Physiol. 1953; 121: 1-27.

Whittaker SRF Winton FR.
The apparent viscosity of blood flowing in the isolated hindlimb of the dog and its variation with corpuscular concentration.
J Physiol. 1933; 78: 339-369

Wood DJ, Bishara R, Darke SG.
The value of perioperative Doppler ankle systolic pressure measurements in reconstructive arterial surgery.
Br J Surg. 1985; 72: 533-536.

PERIPHERAL RESISTANCE MEASUREMENT Ref

Yao ST, Hobbs JT, Irvine WT.
Ankle systolic pressure measurements in arterial disease affecting the lower extremities.
Br J Surg. 1969; 56: 676-679.