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Sources of Error in Intra-arterial Pressure Measurements Across a Stenosis

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Objective: *To investigate potential errors associated with different techniques of intra-arterial pressure measurement at angiography.*

Materials and methods: *An experimental model of an arterial stenosis was developed. Experiments were performed to assess the relevance of catheter position, catheter direction and catheter type on the recorded intraluminal pressure. Trans-stenotic pressure gradients were recorded with and without angiographic catheters crossing the stenosis.*

Results: *At physiological flow rates angiographic catheter type does not influence the recorded pressure. At high flow rates through tight stenoses there is a significant catheter-related difference in recorded pressure adjacent to a stenosis. Downstream pressures may be altered by up to 85 mmHg when standard angiographic catheters are placed across a stenosis.*

Conclusion: *The different techniques employed to measure pressure differences across a model stenosis may introduce significant errors up to 85 mmHg. Care must be taken when pressure measurements alone are used to interpret the clinical significance of a stenosis. In low flow conditions there may not be a detectable pressure gradient across a 95% stenosis.*

Key Words: Angiography; Haemodynamics.

Introduction

Endovascular intervention requires objective evidence of the haemodynamic significance of a lesion before and after treatment. Measurement of the pressure gradient across an arterial stenosis provides a more precise assessment of the haemodynamic relevance of the lesion than multiplanar angiography.[1] There is no standardised technique for recording intra-arterial pressure gradients and the aim of this study is to investigate potential errors that may arise from current techniques using an experimental model of an arterial stenosis.

The pressure gradient across an iliac stenosis can be recorded by three methods; if bilateral femoral access has been established, then the aortic pressure can be measured by a catheter from the contralateral groin and the downstream pressure in the iliac artery can be measured through an ipsilateral sheath. Using this technique no catheter is placed across the stenosis. However, if unilateral access only is available then simultaneous recording requires a catheter placed across the stenosis to measure upstream pressure. A catheter passed through a stenosis will further reduce the cross-sectional area and might be expected to alter the flow rate and downstream pressure. The third approach, also with unilateral access, is a pullback technique where the catheter is pulled through the stenosis while continuously recording pressure.

A haemodynamically significant arterial stenosis causes a velocity increase and associated turbulence over a short distance downstream of the stenosis.[2] A positional variation in the recorded intraluminal pressure might therefore be anticipated. Theoretical considerations suggest that endhole catheters may record different intraluminal pressures compared to catheters with sideholes due to flow induced pressure changes and local recirculation. In particular, unless the tip of the catheter has its opening at right angles to the stream, the pressure recorded is not accurately the pressure existing at that point in the blood because an endhole only catheter facing against the flow results in the conversion of kinetic energy at that point to pressure energy.[3] The measured pressure then exceeds

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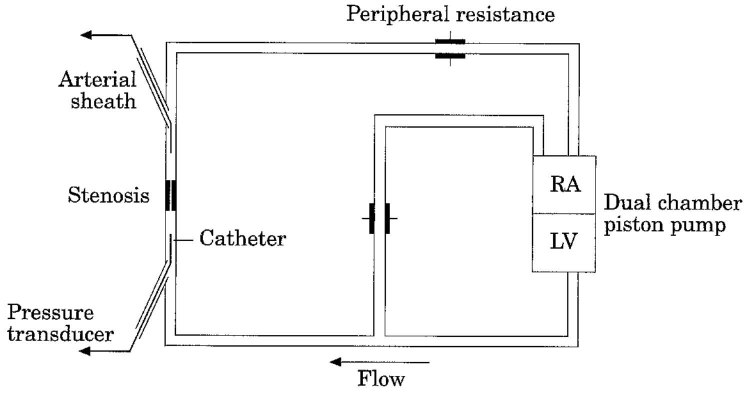

Fig. 1. Experimental model of an arterial stenosis.

the true pressure by 1/2 ρ v^2 where ρ, v denote the density of the blood and blood velocity respectively. When the catheter faces downstream, the recorded pressure is lower than the true pressure by 0.8 ρ v^2.

Accurate pressure gradient measurement requires simultaneous upstream and downstream recording to allow for beat-to-beat variations in arterial pressure and to accommodate the transitory pressure changes following pharmacological vasodilation.[4,5] Simultaneous pressure recording demands either bilateral femoral artery catheters or an ipsilateral sheath with the catheter passed via the sheath through the stenosis, and previous work has suggested that if an insufficient gap exists between the catheter and the sheath then there may be a reduction in the observed femoral artery pressure measurements.[6] Previous work using a canine femoral artery angioplasty model also suggests that when a catheter is placed across a stenosis the true pressure gradient is overestimated in a predictable manner which is dependent on the ratio of the catheter diameter to stenosis diameter.[7]

It is therefore likely that the measurement technique may cause variation in the recorded pressure gradient. The effect of each of the three methods and catheter direction, used to measure the pressure on the recorded gradient, was determined.

Materials and Methods

An experimental model of an arterial stenosis was developed. The experimental circuit (see Fig. 1) comprised a mechanical valved pulsatile pump and silicone tubing (8 mm internal diameter and 2.3 mm wall thickness). The stroke volume and rate of the pump could be varied to alter the flow rate in the circuit. The pump rate (76 strokes/min) was maintained during the experiments. The flow rate was measured by timed collection for 1 min downstream of the stenosis and the values are accurate to ±12.5 ml. Three flow rates were used in all experiments – approximately 300 600 and 900 ml/min – to mimic resting, moderate and hyperaemic iliac arterial flow.

The percentage stenosis is defined as the percentage internal cross-sectional area reduction of the lumen of the silicone tubing. A set of graded stenoses was made from segments of perspex rod; 23 mm length segments were bored using different size drill bits to provide the following varying cross-sectional area stenoses, 44%, 80% and 95%, corresponding to 25%, 55% and 78% diameter stenoses. Arterial sheaths (8-French) were bonded into the circuit on either side of the stenosis using silicone adhesive. The sheaths allowed repeated passage of angiographic catheters into the model vessel. The catheters used were straight angiographic catheters that had either an endhole only (E) or an endhole and four sideholes (E+S) in a spiral distribution extending 12 mm from the tip of the catheter. A sideholes only (S) catheter was created by sealing the endhole of one of the end and sidehole catheters.

The intraluminal pressure was recorded from the catheter or sheath using P10 pressure transducers (Gould Inc) and a calibrated Horizon 2000 (Mennen Inc) pressure monitor. The measurement catheter length was 1 m and the internal diameter 0.088 mm. The resonant frequency of the measurement system was therefore significantly higher than the harmonic content of the pressure signal (estimated as 4 Hz, corresponding to the third harmonic of the pump frequency). The recorded measurement at each position was the mean of three readings and the reproducibility of each measurement was ±2 mmHg. The upstream pressure was maintained throughout at physiological levels (systolic: 100–160, diastolic: 80–110 mmHg). The fluid in the circuit was water and therefore the possible effects of increased viscosity associated with blood have not been stimulated. However, fluid flow in vessels of this diameter and at these viscosities will be dominated by inertia rather than viscosity and the kinetic energy per unit volume will therefore be the same for a given velocity, since the densities of blood and water are similar. Peripheral resistance in the circuit was created by a gate clamp downstream of the stenosis and this remained constant, being set so as to produce typical vessel flow rates of 200–900 ml/min at pressures in the range (systolic: 100–160, diastolic: 80–110 mmHg).

The following sequence of measurements was performed;

Experiment 1. The intraluminal pressure was recorded at 1 cm intervals for 10 cm both upstream and downstream of the stenosis with each catheter type.

Experiment 2. Intraluminal pressures were recorded at the same position with two catheters facing in opposite directions. This was repeated for each catheter type.

Experiment 3. The pressure was recorded from the sidearm of the sheath and also from a catheter of varying size passed through the sheath.

Experiment 4. The pressure gradient was recorded by three methods;

ΔP_1. The upstream pressure was recorded from the upstream sheath and the downstream pressure recorded from the downstream sheath. There was no catheter across the stenosis.

ΔP_2. The upstream pressure was recorded using a catheter – 4, 5, 6, or 7 F – passed through the stenosis from the downstream sheath. The downstream pressure was recorded from the sidearm of the downstream sheath.

ΔP_3. The upstream pressure was recorded from a catheter passed through the stenosis from the downstream sheath. This catheter was then pulled back across the stenosis to record the downstream pressure.

The significance of differences between the measurements was assessed using the paired *t*-test and by comparison with the maximum range of the measurements.

Results

Experiment 1

The intraluminal pressure upstream from the stenosis was not affected by the position of measurement and there was no variation between the three angiographic catheter types. The downstream pressure readings were not significantly affected by position of measurement or catheter type for all flows when using the 44 and 80% stenoses. With the 95% stenosis there was no significant positional or catheter-related variation at flows up to 520 ml/min, since the variation was within the maximum range of the measurements (Fig. 2). At higher flows – 650 and 900 ml/min (Figs 3, 4) – there was a significant variation in recorded downstream pressure within 2 cm of the stenosis. This effect was most marked with the endhole only catheter, though the pattern of variation at a greater distance from the stenosis was less pronounced; at 650 ml/min (Fig. 3) the sidehole catheter gave significantly higher readings than the end-and-sidehole catheter, while at 900 ml/min, the end and end-and-sidehole catheter were significantly different.

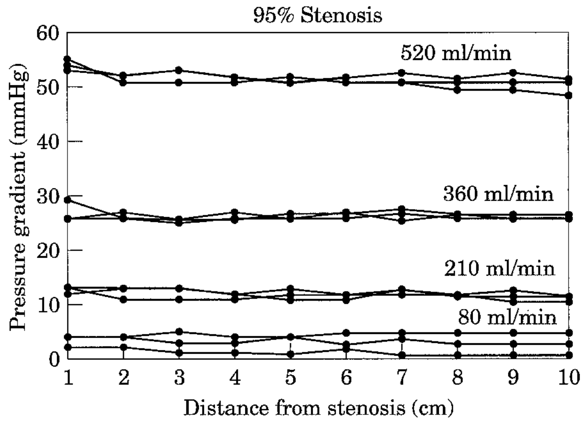

Fig. 2. Graph of pressure gradient plotted against the distance downstream of the 95% stenosis at different flow rates. The three different catheter-types were used at each flow rate. Differences between the measurements made by the different catheters within the maximum range of measurements (±2 mmHg).

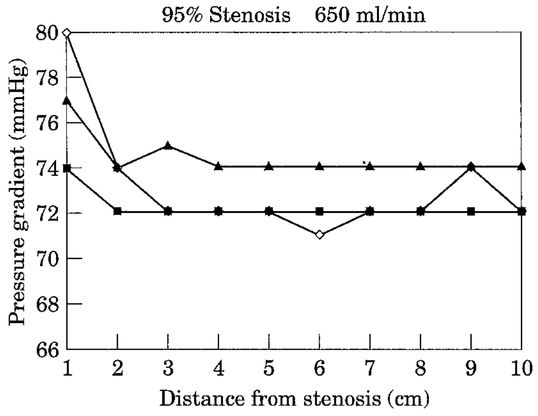

Fig. 3. Pressure gradient plotted against distance from the 95% stenosis at a flow rate of 650 ml/min. Three catheter types, **E** = endhole only, **E + S** = end + sideholes, **S only** = sideholes only catheter. Maximum range of measurements ±2 mmHg. Significant difference between S and E+S measurements (p<0.001). (◇) E; (■) E+S; (▲) S only.

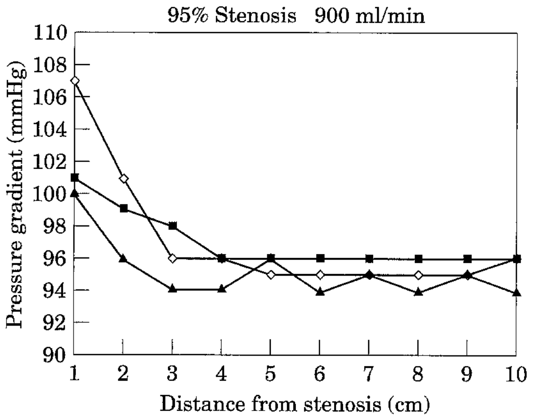

Fig. 4. Pressure gradient plotted against distance from the 95% stenosis at a flow rate of 900 ml/min. Three catheter types, E = endhole only, E + S = end + sideholes, **S only** = sideholes only catheter. Maximum range of measurements ±2 mmHg. Significant difference between E and E+S ($p<0.001$) only. (◇) E; (■) E+S; (▲) S only.

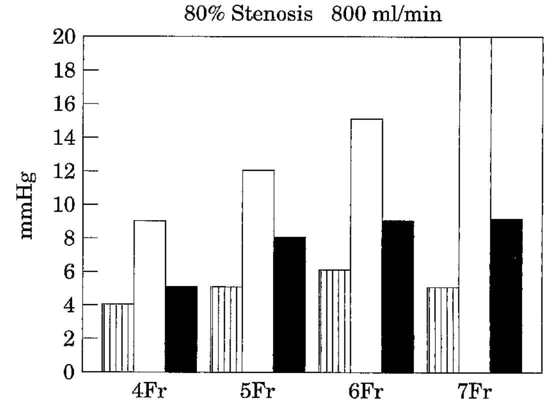

Fig. 5. Pressure gradient at 800 ml/min across the 80% cross-sectional area (55% diameter) stenosis. The gradient was recorded using the three techniques ΔP_1, ΔP_2, ΔP_3 (see materials and methods) with 4, 5, 6 and 7 F catheters. Maximum range of measurements ±2 mmHg (▥) ΔP_1; (□) ΔP_2; (■) ΔP_3.

Experiment 2

The pressure recorded from two catheters at the same position downstream of the stenosis facing in opposite directions showed no significant difference with varying stenosis diameter, flow rate or catheter type.

Experiment 3

The pressure recorded from the sidearm of the sheath was equal to that of a catheter passed through the sheath to a position downstream of the stenosis for all catheters sizes – 4, 5, 6 and 7 F – passed through the 8 F sheath, to within the limits of reproducibility.

Experiment 4

There was no pressure gradient across the 44% stenosis even when a 7 F catheter was passed through the stenosis. At low flow conditions there was no significant gradient across the 80% stenosis and no change in gradient when 4–7 F catheters were placed across the stenosis, within the limits of reproducibility. At high flow – 800 ml/min – the presence of a catheter across the 80% stenosis did cause an additional pressure drop which increased with increasing catheter size (Fig. 5). There was a relatively large increase in the pressure gradient when 4 and 5 F catheters were placed across the 95% stenosis at low flow (Fig. 6); at 200 ml/min there was a 8 mmHg gradient across this stenosis using technique ΔP_1. This increased to 55 mmHg when a 4 F catheter, and 93 mmHg when a 5 F catheter, was placed across the stenosis and the gradient measured using technique ΔP_2. In each case, the lowest pressure gradient was recorded using technique ΔP_1.

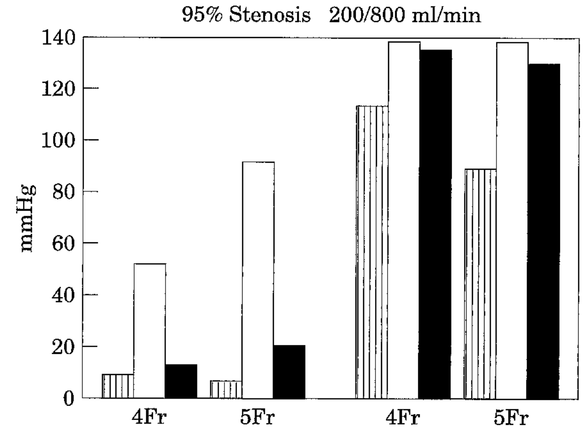

Fig. 6. Graph of pressure gradient across the 95% cross-sectional area (78% diameter) stenosis with flow rates of 200 ml/min (left columns) and 800 ml/min (right columns). The gradient was recorded using the three techniques ΔP_1, ΔP_2, ΔP_3 (see materials and methods) with 4 and 5 F catheters. Maximum range of measurements ±2 mmHg (▥) ΔP_1, (□) ΔP_2; (■) ΔP_3.

Discussion

Measurement of the trans-stenotic pressure gradient is an invaluable adjunct in management of iliac arterial lesions. The pressure gradient not only helps in the initial decision to treat an iliac lesion but also is used to evaluate the result of angioplasty and to assess the need for stent deployment.[8] It is thus important that the technique of intra-arterial pressure measurement does not introduce error that could result in under- or over-estimation of the significance of an arterial stenosis. Previous work[7] suggests that measured pressure gradient $=\mathrm{K} \times$ true pressure gradient where $\mathrm{K}=0.25\, e^{4.47\mathrm{R}}$ and R is the ratio of catheter-to-stenosis diameter. This relationship therefore suggests the measured gradient may exceed the true gradient by a factor of up to 8 (for $\mathrm{R}=0.8$, maximal in these experiments).

In reality, the resistance of the stenosis is the key parameter and this is given by the ratio of the pressure gradient to the flow through the stenosis. There is, however, no readily available accurate method for measuring the arterial flow rate in the angiography laboratory. Although pressure gradient measurements alone are commonly used in clinical practice, it is important to recognise that if *in vivo* measurements are made during conditions of low flow – for example, with poor run-off vessels and low cardiac output – then no significant gradient may be recorded across a potentially important iliac stenosis. However, a significant pressure drop may result from the increased limb blood flow due to the decreased peripheral resistance that follows infrainguinal bypass surgery.

The magnitude of the gradient which is deemed significant has been interpreted variously by different authors.[5,9] A resting peak systolic pressure gradient of 10 mmHg and a peak systolic gradient of 20 mmHg after vasodilation are considered to be significant.[5] Brewster[10] defined significant lesions as those that generated a resting systolic pressure difference of 5 mmHg or a decrease in femoral artery pressure of more than 15% with reactive hyperaemia. Other authors deem a resting systolic gradient of 29 mmHg as indicative of 50% or more iliac stenosis.[9]

Angiographic catheters may have a single endhole or an endhole and multiple sideholes. Some authors recommend the use of an endhole only catheter for recording intra-arterial pressure.[11] The endhole may be partially or completely occluded when it abuts the irregular wall of an atheromatous vessel and therefore records erroneous pressure values. Fluid mechanical considerations[3] confirm a possible variation in the pressure recorded from endhole and sidehole catheters as noted in the introduction. Our results (Figs 3, 4) indicate that at physiological flow rates and pressures there are small but statistically significant differences between the pressure gradients recorded by the different catheter types but no clear pattern emerged for distances more than 2 cm from the stenosis, suggesting that this effect is insignificant and endhole only, and end-and-sidehole catheters are interchangeable; a flow rate of 300 ml/min in tubing of internal diameter 8 mm is associated with a mean velocity of approximately 10 cm/s which is equivalent to a pressure of 4.9 Pa (0.037 mmHg). A flow rate of 900 ml/min yields a mean velocity of 30 mm/s and an associated pressure of 0.34 mmHg. These small theoretical differences are therefore consistent with our observations, provided the catheter measurement is not unduly influenced by a high velocity jet of fluid from the stenosis. Adjacent to a stenosis, at supra-physiological flow rates, there is a significant difference in the pressure recorded by E and E + S catheters. The endhole only measurements are up to 10% less than the E + S measurements when the catheter is within 2 cm downstream of a 95% stenosis with flow rates of 900 ml/min. This is likely to be due to areas of turbulence and flow recirculation adjacent to the stenosis. The E + S catheter has four sideholes in a spiral distribution which extend 12 mm from the tip of the catheter. This catheter therefore records the mean pressure over the hole-bearing segment of catheter and is likely to be less affected by juxtastenotic turbulence. The variation between the catheters occurs at pressure and flow rates which are unlikely to be achievable *in vivo*. The pressure gradient recorded by both catheters was already clinically significant and the variation would not be sufficient to result in different management of the stenoses.

The catheter direction was not a source of error and this result has relevance in the recording of intra-arterial pressure distal to an iliac stenosis using a catheter passed over the bifurcation from the contralateral groin. In that situation no error would be expected due to catheter direction, but a potential error may arise due to the passage of the catheter through a stenosis.

The sidearm of the 8 F sheath recorded accurate intraluminal pressure despite the passage of catheters up to 1 F less than the diameter of the sheath. This suggests that simultaneous recording of pressure from the sidearm of the sheath and a catheter passed upstream of the stenosis through the lumen of the sheath is reasonably accurate.

Experiment 4 confirms that the passage of standard angiographic catheters through an arterial stenosis can significantly affect downstream pressure. In clinical practice this effect may be sufficient to alter the interventional management of the patient. The optimum method of measuring a pressure gradient involves simultaneous pressure recording from bilateral femoral artery catheters without crossing the stenosis. Unilateral access does allow simultaneous measurement. If there is no significant pressure gradient despite having placed a catheter across a stenosis, then this is an adequate result. However, if a pressure gradient is recorded in the presence of a trans-stenotic catheter than it is important to consider the possibility that some of the measured pressure drop may be due to the technique. The pullback technique does allow the gradient to be measured with unilateral access only without interfering with the stenosis when recording downstream pressure. The disadvantages are that the measurements are sequential rather than simultaneous and cannot compensate for error due to beat to beat variation in blood pressure and transitory pressure changes after vasodilatation. One further disadvantage, particularly relevant when assessing the gradient after angioplasty, is that one then needs to recross the fresh angioplasty site if a significant residual gradient exists and repeat angioplasty or stenting is necessary. This disadvantage of the pullback technique may potentially be avoided if the pressure is recorded using a 0.018 inch pressure guiding wire (Radi Medical Systems, Uppsala).[12] This device cannot generally replace fluid-filled systems and microtip transducer catheters for recordings of left ventricular and aortic pressure, or for absolute pressure measurements in low-pressure areas such as the right heart chambers, veins, and pulmonary vessels for pressure gradient measurements. The measurement errors do, however, tend to cancel out when gradients are calculated. The small size causes less gradient augmentation in narrow stenoses than with fluid-filled systems and allows insertion through narrow stenoses. This device may therefore permit a potentially more accurate measurement of the transtenotic gradient.

In conclusion, intra-arterial pressure measurements will continue to form an essential role in the assessment of stenotic arterial disease. We would caution angiographers to be aware of the limitations of the technique and in particular to be aware that a catheter placed across a stenosis may introduce a significant error into the measurement of the pressure gradient.

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