Endovascular Pressure Measurements: Validation with a Pulsatile Flow Model and Haemodynamic Assessment of Brain AVMs

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Summary

Intravascular pressure measurements for several types of endovascular catheters were obtained in an in vitro model to validate the pressure readings obtained during the interventional procedures of brain AVM embolization.

An experimental model was used where the beat rate, flow and pressures were as close as possible to the average human values of interest. It is shown that the corrections increase with the decreasing inner diameter of the catheter used and with increasing vascular pressure. We have also shown that there were no differences between measurements made with the catheter in the direction of flow or against it. An average pressure reading corrections for the various microcatheters to compensate the readings obtained during in vivo monitoring is presented.

The haemodynamic assessment of 81 brain AVMs was performed using the endovascular measurement of arterial pressure in 389 feeding arteries during embolization. Mostly, the feeders' arterial median pressure was half the systemic arterial pressure but there was a wide variability of AV shunts in brain AVMs not only from one brain AVM to another but also within the same brain AVM. Measurement of arterial feeder pressure is an inexpensive, quick and accurate tool to evaluate the type of AV shunts within brain AVM.

Introduction

The use of intravascular pressure measurements is becoming increasingly accepted in the endovascular therapy of arteriovenous malformations (AVMs) in interventional neuroradiology¹⁻²⁰. The interest in pressure measurements arises from studies on the haemodynamic factors that contribute to AVM rupture^{8,11-13, 19} and neurological symptoms¹⁸, the haemodynamic changes induced by embolization^{5,6,9,10,17,20} and the increasingly recognized importance of the physical parameters and mechanisms in cerebrovascular diseases²¹, leading to several attempts to model the haemodynamics of AVMs and their risk of haemorrhage biomathematically²²⁻³⁰.

Pressure measurements are obtained by means of standard intravascular catheters connected to a pressure transducer that is in turn connected to a pressure monitoring system, giving real time readings as the catheter is being used. Although some work has already been done to check the validity of these pressure measurements⁷ our study was started to extend this approach to more types of catheters (and microcatheters) and to look for pressure differences between different catheters as a function of intravascular pressure.

In the first phase of our work, we validated the pressure measurements by using an in vitro

Figure 1 Overall setup of the experimental pulsatile model.

model, reproducing as close as possible the conditions in the body. This allowed us to have reproducible and measurable conditions with access for the catheters allowing us to register prospectively the feeding arteries blood pressure of brain AVMs in the second phase of our work.

Material and Methods

1. Validation of endovascular pressure measurements with a pulsatile flow model

To simulate human conditions as closely as possible *in vitro* we developed an experimental pulsatile model where the beat rate, flow and pressures were adjusted to be as similar as possible to average human values. The model^{31,32} consisted of a network of tubes, a peristaltic pump and a highly viscous circulating fluid. The overall setup of the experimental pulsatile model is shown diagrammatically in figure 1. Our purpose was not to mimic the cerebral vasculature but rather to have a series of different resistance tubes to allow us to measure pressure in different conditions.

A network of bifurcating tubes was placed inside a plastic box which served as a reservoir

filled with the circulating fluid. The two main tubes gave way to eight smaller diameter tubes. The liquid was aspirated from the reservoir by means of a pump which forced it to circulate through the two tubes connecting to the network. At the exit of the pump we inserted an adjustable valve which allowed us to control the pressure at the network by diverting more or less flux from it. To produce a pulsatile flow we used a Bredel SP10 peristaltic pump, which allowed us to vary the beat rates from 14 to 115 beats per minute. Since the pump used gave us the typical profile of a peristaltic pump instead of the pressure profile characteristic of the normal human blood pressure we introduced an artificial “aorta” to simulate the elasticity of the aorta giving us a pressure profile more closely approximated to reality.

This artificial “aorta” consisted of a section of rubber tube giving us an elasticity that produced an increase in the minimum pressure during the cycle, as opposed to the zero observed without the “aorta”.

To achieve a viscosity comparable to that of blood we used a blood mimicking fluid. Although several companies sell such fluids we preferred to prepare our own blood flow sub-

Figure 2 Variation of the average pressure measured in the microcatheter as a function of the distance from the carrier tip.

stitute by mixing Xanthan gum with water, as referred by Mann et Al³³, in a proportion to achieve a liquid with a 3.5 centipoise viscosity, close to that of blood. For our working condi-

tions we calculated the Reynolds number to be 900 for the Xanthan solution, compared to 3400 for water, giving us a fairly laminar flow in the tubes we were using for the measurements.

Table 1 Inner and outer catheter diameters

Catheter / Microcatheter	Inner Diameter		Outer Diameter	
	mm	inch	F number	mm
Headway 6F (CathNet-Science Paris, France)	1.49	0.060	6 F	2.00
Headhunter 4F (Cordis, Johnson & Johnson, NV/SA, U.S.A.)	1.00	0.040	4 F	1.33
Tracker 10 (Boston Scientific Corp., Target, Los Angeles, U.S.A)	0.25	0.010	2.5 F	0.83
Tracker 18 (Boston Scientific Corp., Target, Los Angeles, U.S.A)	0.46	0.018	2.7 F	0.90
Magic 1.2 (Balt, Montmorency, France)	0.20	0.008	1.6 F	0.55
Magic 1.5 (Balt, Montmorency, France)	0.31	0.012	1.9 F	0.65
Magic 1.8 (Balt, Montmorency, France)	0.36	0.014	2.4 F	0.80
Sense ML 2.8 (CathNet-Science Paris, France)	0.41	0.016	1.9 F	0.66
Rapid Transit (Cordis, Johnson & Johnson, NV/SA, U.S.A.)	0.53	0.021	2.3 F	0.70

Figure 3 Pressure reading for each microcatheter as a function of the pressure in the carrier.

Figure 4 Pressure difference between the readings taken with the microcatheter and the carrier as a function of the pressure in the carrier.

All the pressure measurements were obtained with Baxter Uniflow pressure transducers with their signals amplified and recorded on a Mac Lab system for haemodynamic monitoring by Marquette Medical Systems. The pressure measurements were obtained on a variety of catheters. The names and inner and outer diameters of the catheters used are indicated in table 1. The pressure measurements were obtained simultaneously in the micro-catheter and carrier catheter.

To test the difference in viscosity we measured pressures differences and flow along the model tubes with distilled water and our Xanthan fluid, without the artificial aorta. To evaluate whether the injection of contrast with its different viscosity would alter the

Figure 5 Total pressure differential values histogram.

Table 2 **Brain AVM characteristics**

Patients	81
	Masc: 48 (59%) Fem: 33 (41%)
	Mean age: 33.5 (Std dev 15.34) [8 months; 66 years]
Total brain AVM	81
	Supratentorial 74 (91%)
	Infratentorial 7 (9%)
Clinical Presentation	Haemorrhage: 27 (33%)
	Other: 54 (67%)
Size	< 3 cm: 33 (41%)
	3-6 cm: 45 (55%)
	> 6 cm: 4 (4%)
Topography	Cortical: 4 (5%)
	Cortical-subcortical: 44 (54%)
	Cortical-ventricular: 21 (26%)
	Deep and brain stem: 10 (12%)
	Callosal: 2 (3%)
Spetzler Grade	I: 5 (6%)
	II: 27 (33%)
	III: 32 (40%)
	IV: 14 (17%)
	V: 3 (4%)
Deep venous drainage	Present: 39 (48%)
	Absent: 42 (52%)

Figure 6 Mean Brain AVM pressure differential values histogram and normal curve.

readings obtained in the pressure transducer, we filled the microcatheter with different fluids while maintaining exactly the same flow conditions in the model and filling the carrier-catheter with physiologic fluid (normal saline) to give a reference value. To test if the localization of the microcatheters with respect to the carrier-catheter would affect the pressure measurements, we obtained simultaneous measurements on the carrier and microcatheter for several distances between the end points of the two catheters. To assess whether the catheters give the same readings when measuring pressures with the end opening in the direction of the flow and against the flow we placed two identical catheters introduced from different sides of the model, with their end openings at a distance of 1 cm. To evaluate if there was any change in the mean pressure, mean pressure differences and pressure wave profile with the diameter of the microcatheter, we simultaneously obtained pressure readings from microcatheters with different inner-diameters at different pressures.

2. Brain AVM feeding arteries pressure measurements

We prospectively used mean arterial feeder artery pressure measurements during brain AVM embolization and evaluated 81 consecutive patients with brain AVMs embolized at the Garcia de Orta Hospital – Portugal. The general characteristics of the population and brain

AVMs evaluated are described in table 2.

The haemodynamic assessment was performed during the endovascular procedures by measuring the mean blood pressure inside the brain AVMs feeders as close to nidus as possible, just before performing embolization with NBCA, the only embolic agent used. The arterial feeding artery pressure was recorded with strain gauge pressure transducers relative to the right atrium, displayed in real time on a monitor and recorded with a Mac Lab System. The patients were under general anaesthesia or neuroleptic analgesia and the arterial pressure values during the procedure were kept in the same range as patients' baseline values. The values obtained from ex-

ternal carotid artery and from dural branches of the internal carotid artery (ICA), vertebral artery (VA) were excluded from the analysis.

The pressure differential (PD) was calculated by the simultaneous measurement of the mean systemic (recorded from an arterial line) and feeder arterial pressures. The values of the mean pressure of arterial feeders were recorded after flushing the microcatheter with normal saline and adapting the microcatheter to the transducer. The transducer was previously set to zero at the level of the right atrium. These values were validated by the use of the correction factor specific to each type of microcatheter used.

The value of the PD was obtained according to the following formula: $PD = mSAP - mFAP / mSAP$ (PD-pressure differential; mSAP- mean systemic arterial pressure; mFAP- mean feeder arterial pressure). The pressure differential (PD) values were classified in 4 grades: Grade I - $PD < 0.3$; Grade II - $PD [0.30; 0.45]$; Grade III - $PD [0.45; 0.60]$; Grade IV - $PD > 0.6$.

Results

1. Validation of endovascular pressure measurements with a pulsatile flow model

Maintaining a constant flow and using the same tubes we found pressure increases up to four times those expected from simple physics considerations with the use of fluids of different viscosity. We have shown that the injection

Figure 7 Total and Mean brain AVM pressure differential grade distribution.

of contrast alters the pressure readings, as it can be seen from table 3 demonstrating the pressure reading increase with higher viscosity of the fluid inside the catheter.

Our results have shown that it is not critical where the microcatheter tip is with respect to the end of the carrier, since no difference was found for a difference in distance from 4 to 5 cm (figure 2).

For a range of different pressures the readings and at different locations of the opening the values obtained were always the same showing that there is no difference whether the measurement is obtained on the arterial (in the flow direction) or on the venous side (against the flow direction).

We observed an increase in the mean pressure differences between the microcatheter and the carrier as the inner-diameter of the microcatheters decreased. There was also a pressure profile change: the pressure wave amplitude decreased with decreasing diameter as the absolute pressure was kept constant. Figure 3 shows the carrier-catheter and microcatheter pressure measurements, obtained simultaneously at different pressures, plotted against each other to obtain a graph of the pressure reading for each microcatheter as a function of the pressure in the carrier. Figure 4 shows the

difference in pressure between the pressure of the microcatheter and the pressure of the carrier as a function of the pressure in the carrier.

From the above results we deduced an approximate pressure difference between the carrier-catheter and the microcatheters for the pressure range of interest in the human case (60 to 120 mm Hg). This is obtained by calculating for each catheter the average mean pressure for this range from the graph.

The values obtained are shown in table 4. These values were used to correct the mean arterial pressures obtained from different microcatheters.

2. Brain AVM feeding arteries pressure measurements

We evaluated the mean arterial pressure of 389 feeders corresponding to 96% of the total amount ($n=414$) of pial brain AVM feeders embolized with NBCA, resulting in a mean evaluation of 4.8 feeders per AVM/patient. The pressure differential (PD) values were obtained according to the abovementioned formula. The total brain AVM population measurements (total PD values) and the mean pressure differential for each brain AVM obtained by the arithmetic average of the PD values obtained in the same brain AVM (mean

Table 3 Variations in the measurements of pressure (mm Hg) in microcatheters filled with fluids with different viscosity

		Tracker 18	Magic 1.2
Headhunter 6F carrier	w/ physiological fluid	103	101
Microcatheter	w/ physiological fluid	106	117
	w/ Xanthan solution	117	140
	w/ contrast	134	200

Table 4 Microcatheter-specific correction values

	Microcatheter pressure reading (mmHg)					
	50-120	20-40	40-60	60-80	80-100	100-120
	Mean Correction Factors* (mmHg)					
Microcatheter	Global	Specific				
Magic 1.2	13	18 ± 2	16 ± 2	14 ± 2	13 ± 2	11 ± 2
Tracker 10	9	11.8 ± 0.7	10.9 ± 0.7	10.0 ± 0.7	9.1 ± 0.8	8.2 ± 0.8
Magic 1.5	8	8.6 ± 0.5	8.3 ± 0.6	7.9 ± 0.6	7.6 ± 0.7	7.2 ± 0.8
Magic 1.8	6	8 ± 1	8 ± 2	7 ± 2	7 ± 2	7 ± 2
Sense ML 12	5	5.7 ± 0.6	5.4 ± 0.6	5.1 ± 0.7	4.8 ± 0.8	4.5 ± 0.9
Tracker 18	3	4.0 ± 0.7	3.9 ± 0.8	3.8 ± 0.9	4 ± 1	4 ± 2
Transit 3	3	3.5 ± 0.4	3.5 ± 0.4	3.5 ± 0.5	3.4 ± 0.5	3.4 ± 0.5
* The correction factor value should be subtracted from the pressure value recorded by the microcatheter (mmHg).						

Table 5 Pressure differential (PD) values

Measurements		Total: 414 Valid: 389 (96%) Missing: 25 (4%)	
		Total PD values	Mean Brain AVM PD value
Mean		0.4796	0.4625
Standard deviation		0.1701	0.1190
Median		0.5061	0.4750
Range of pressure differential value		0.05 – 0.88	0.14 – 0.7
Percentile	P 25	0.3758	0.3700
	P 50	0.5061	0.4750
	P 75	0.6102	0.5575
Values distribution		Non normal	Normal

Figure 8 Type of brain AVM arterial feeders catheterized. Perforator vert-bas- perforator artery branch of the vertebro-basilar system; Cortical vert-bas- cortical artery branch of the vertebro-basilar system; Perforator carotid- perforator artery branch of the internal carotid artery; Cortical Carotid- cortical artery branch of the internal carotid artery.

brain AVM PD value) are described in table 5 and illustrated in the figures 5 and 6. Taking into consideration all the values obtained, the majority ranged from 0.37 to 0.61 (percentiles 25-75) with a median value of 0.5061, demonstrating that the feeders arterial median pressure is generally half the systemic arterial pressure. For the mean brain AVM pressure differential, most of the values were in between 0.37 and 0.55 (percentiles 25-75), representing a smaller interval of values. Again, the median value was much closer to half the value of the systemic arterial pressure. The classification in pressure differential grades showed that 69 (17%) feeders belonged to grade I, 73 (18%) to grade II, 137 (35%) to grade III and 110 (28%) to grade IV and that the mean pressure differential of the brain AVM was classified in grade I for six (7%) cases, grade II for 29 (36%) cases, grade III for 35 (43%) cases and Grade IV for 11 (14%) cases (figure 7). The type of arterial feeders that were super-selectively catheterized is shown in figure 8.

Discussion

The main interest of this work consists in the validation of pressure measurements made in vivo to make sure that the correct value of the pressure at a particular point is directly measured by the microcatheters, to be subsequently used during endovascular interventional procedures. This validation of pressure readings

obtained with microcatheters is very important since arterial pressure in feeding arteries is a marker of the haemodynamics status of malformations and valuable information on the patients' condition with importance for the treatment strategy may be deduced from these measurements.

To this effect we set up all the parameters in the model to the same values to make sure that at a particular point in the tube network we had a constant value of mean pressure and then we introduced the different microcatheters and recorded the different values measured at exactly the same point. To further check the value of the pressure we read the pressure value in the carrier-catheter simultaneously, enabling us to monitor whether the carrier value stayed reliably constant to be used as a reference.

Our results have shown that the pressure wave amplitude decreases with decreasing diameter supporting the standard assumption that what matters in interventional pressure measurements is the mean pressure of the pressure wave profile. They have also demonstrated that the viscosity of the fluid inside the microcatheter drastically changes the readings obtained through this type of measurement. Therefore, it is highly recommended that any catheter used to inject contrast should be thoroughly rinsed with normal saline before connecting it to a pressure transducer for pressure measurements. Moreover, it makes no difference whether the catheter is placed on the ar-

terial or on the venous side and it is not critical where the catheter tip is with respect to the end of the carrier.

To make these results more useful to the neuroradiologist in the angiography room, it is better to have a mean value for the pressure correction for each catheter when used within a realistic range of pressures. We routinely use the validated feeding artery pressure measurements to quantify the shunt flow in brain AVM just before performing embolization with the liquid occlusive embolic agent NBCA.

To be able to quantify the flow in the feeding arteries we use the following formula: $PD = mSAP - mFAP / mSAP$ (PD-pressure differential; mSAP- mean systemic arterial pressure; mFAP- mean feeder arterial pressure). Taking into consideration the Poiseuille law, this equation would give us an indirect estimation of the flow inside the feeding artery. To make the values obtained more familiar during embolization we have classified them into four grades, namely Grade I - $PD < 0.3$; Grade II - $PD [0.30; 0.45]$; Grade III - $PD] 0.45; 0.60]$; Grade IV - $PD > 0.6$. According to this classification, it is simple to understand that in grade I feeders the arterial feeders' pressure is high, the pressure differential low and that this generally represents low flow. Instead, in grade IV feeders the feeders' pressure is low, the pressure differential is high and generally the feeders' flow is higher.

We were able to measure the pressure in more than 95% of catheterized feeders and the values were closely related to the qualitative impression of the superselective contrast injections with the microcatheter. However, whenever there was a conflicting impression from the qualitative and quantitative observations, the pressure differential measurements were always more accurate. In exceptional circumstances we could not obtain accurate values, namely when the microcatheter tip was in contact with the vessel wall and when there was microcatheter induced vasospasm.

The pressure values and pressure differentials obtained showed that there is a wide variability in the type of AV shunts in brain AVMs. This variability is not only from one brain AVM to another but also inside the same brain AVM. The arterial pressure decreases progressively along the arterial tree and the feeder pressure is low. This is the result of the low resistance of

the AV shunts^{1,5,6, 7,8,16,21}. Our results are concordant with these previous haemodynamic studies in brain AVM, showing that that mean feeding arteries pressure is decreased, being generally less than 50% of mean systemic arterial pressure, especially in larger AVMs^{2,3,6,7,14,19}. Instead, patients without brain AVMs tend to have higher arterial pressures at the same level, namely ratios of 0.75 to 0.85 in M1-M3 and P1-P3 levels⁹ and up to 0.9 at the level of pial or M5 arteries³⁴⁻³⁷.

The ratio between systemic and feeder arterial pressure is essential for accurate brain AVM haemodynamic analysis. Firstly, because we have also witnessed that the pressure in the arterial feeders generally changes in relation to the systemic blood pressure as observed by other authors^{14,15}. Secondly, because systemic arterial pressure variations are not transmitted in their full magnitude to the feeding arteries which have an intrinsic buffering capability^{14,15}. Lastly, this buffering effect differs according to the type of feeders, namely its baseline pressure, since lower pressure feeders have fewer changes in arterial pressure with increasing systemic pressure in comparison with higher pressure feeders^{14,15}.

Finally, arterial pressure measurements of brain AVM feeders were extremely important for the correct flow judgment and NBCA type of dilution choice without lengthening the embolization procedure. We consider that these measurements may be especially helpful providing an objective evaluation of the AV shunt type.

Conclusions

The validation of the pressure values obtained by microcatheters is needed to obtain correct pressure measurements and this may be accomplished by the use of the microcatheter specific correction values presented. This is of extreme importance for the correct haemodynamic assessment of brain AVMs, namely for future correlations with clinical presentation and morphological features of this type of vascular malformation.

Pressure measurement of brain AVM arterial feeders is an inexpensive, quick and accurate tool to evaluate the type of AV shunts and consequently for correct flow judgment and NBCA type of dilution choice during embolization.

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